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NITROUS OXIDE (N_2O)

emission inventory and options for control
in the Netherlands

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SUMMARY

The study presented in this report was initiated to overview current knowledge on nitrous oxide (N_2O), with the report reviewing atmospheric behaviour of N_2O (chapter 2), global sources and sinks (chapter 3), emissions in the Netherlands in 1990 (chapter 4), options to reduce emissions (chapter 5), and past and future emissions (chapter 6).

N_2O in the atmosphere

Nitrous oxide is one of the natural components of the earth's atmosphere. The atmospheric concentration of N_2O has today reached its highest level in 45,000 years. The increase in atmospheric N_2O, most probably the result of human activities, started this century. Atmospheric concentrations of N_2O are relatively constant throughout the troposphere; this is in line with its long atmospheric lifetime of about 120 years. Concentrations in the northern hemisphere are slightly higher than in the southern hemisphere.

Nitrous oxide, one of the natural greenhouse gases, is responsible for 4-6% of the present radiative forcing. It is a powerful greenhouse gas, with a Global Warming Potential of 170 - 270 (CO_2 = 1). It also contributes to stratospheric ozone depletion; however, to what extent is not clear.

Some formation of N_2O may occur in the troposphere. Three chemical pathways resulting in N_2O formation have been proposed in the literature. Their contribution to atmospheric N_2O is probably small. Nitrous oxide is chemically inactive in the troposphere. Destruction of N_2O takes place in the stratosphere, mainly by ultraviolet radiation.

Global sources and sinks

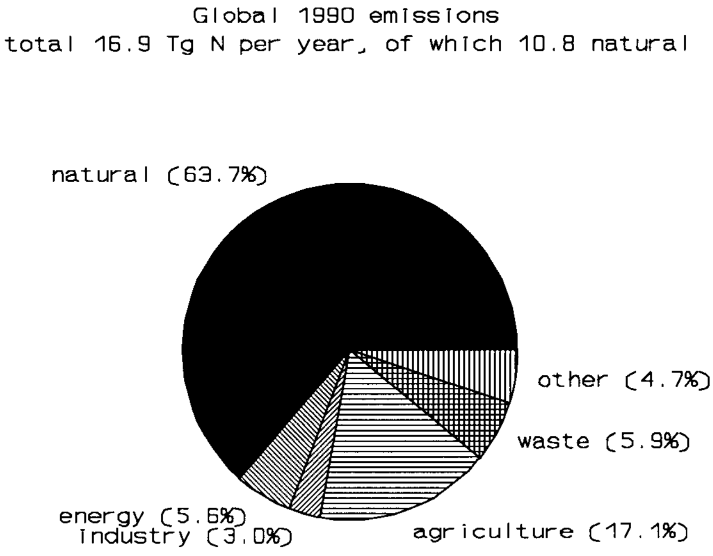
Chapter 3 describes and quantifies global sources and sinks of atmospheric N_2O. A distinction is made between natural and anthropogenic sources and biogenic and abiogenic processes. Most atmospheric N_2O is of biological origin. Biogenic formation of N_2O occurs in soils and waters during nitrification and denitrification. These are biological processes, during which N_2O is formed as an intermediate by-product. Biogenic N_2O formation is enhanced by human activities, in particular by nitrogen input to soils (fertilizers, animal manure and atmospheric deposition). Abiogenic formation of N_2O occurs for example during combustion processes and in the atmosphere. Most abiogenic N_2O formation is the result of human activities such as fossil fuel and biomass burning.

The observed increase in atmospheric N_2O indicates that the present global emissions amount to 16.0 (11.9 - 19.1) Tg N y^{-1}, of which 4.5 (3.9 - 5.1) are anthropogenic. Emission inventories as published in the literature total 16.9 (9.6 - 27.6) Tg N y^{-1}, of which 6.1 (1.5 - 13.9) Tg N y^{-1} are anthropogenic. Thus the total of the published inventories is consistent with the total based on an atmospheric mass balance, but some of the anthropogenic sources may have been overestimated.

Anthropogenic sources of N_2O are from energy (0.9 Tg N y^{-1}), industry (0.5 Tg N y^{-1}), agriculture and land use change (2.9 Tg N y^{-1}), waste (1.0 Tg N y^{-1}), and other sources (0.8 Tg N y^{-1}) (Fig. 1). Activities related to human food production (including land

use change, industrial production of fertilizers and atmospheric formation of N_2O in NH_3 polluted air) are responsible for about 50% of the present global anthropogenic emissions.

Environmental policy measures may affect N_2O emissions in several ways and their net effect is not always obvious: (1) reduction of NOx and NH_3 emissions will decrease enhanced biogenic N_2O emissions induced by atmospheric deposition, (2) NOx reduction techniques may increase N_2O emissions from combustion processes; this is particularly obvious in 3-way catalytic converters in transport, (3) some NH_3-reducing techniques may increase N_2O emissions, e.g. injection of organic fertilizers and HNO_3 addition to manure, (4) measures reducing use of energy, fertilizers, etc, may decrease associated N_2O emission simultaneously.



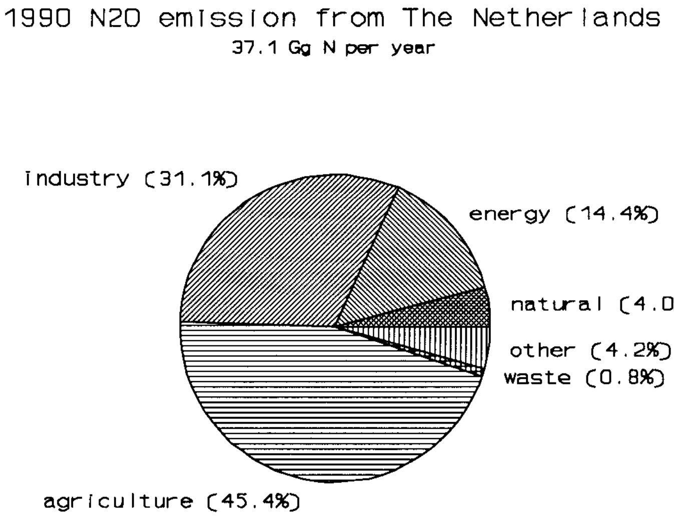


Fig. 1. Global and Dutch emissions of N_2O in 1990.
Dutch emissions are estimated using method II.

Dutch N_2O emissions in 1990: two methods

Chapter 4 describes two methods to estimate country emissions of nitrous oxide to the atmosphere. The two methods are used to to calculate Dutch 1990 emissions.

- The first method (method I) is in development by IPCC/OECD. When applied to the Netherlands, method I results in 1990 emissions of 17 (6 - 38) Gg N y^{-1} or 27 (10 - 60) Gg N_2O y^{-1}. Abiogenic emissions from industry and transport are the most important emissions in the Netherlands in this method.
- The second method (method II) is an update of an existing RIVM methodology, resulting in considerably higher emissions for 1990: 37 (13 - 70) Gg N y^{-1} or 58 (20 - 110) Gg N_2O y^{-1}, with a major contribution from agriculture (Fig. 1).

Method II is considered more appropriate than method I for three reasons.

- Method II includes more sources and is therefore more complete. For instance, emissions as a result of nitrogen leaching from soils, other N loading to surface waters, wastewater treatment, atmospheric deposition of NOx and non-agricultural NH_3, manure in stables, atmospheric formation, and use in anaesthesia are not included in method I. Method II attempts to include all known sources of atmospheric N_2O.
- The method II emission factors have been validated with Dutch research, and may therefore be more appropriate for a Dutch emission inventory.
- Method I clearly underestimates emissions of N_2O when applied to global activity data, most probably as a result of not taking into account all sources and low emission factors.

According to method II, at least 95% of the 1990 emissions are anthropogenic. Important sources are agriculture (45%), industry (31%) and transport (10%). Most of the agricultural emissions are from soils (86%), while surface waters (leaching) and stables contribute 11 and 3%, respectively.

Reduction of anthropogenic N_2O emissions

Chapter 5 describes options to reduce emissions of N_2O. The technical potential of a number of options to reduce N_2O emissions is considered. Their economic potential is, however, not investigated in this study. Volume-type options are only described qualitatively. To date, no policy measures for N_2O have been formulated in the Netherlands.

One technical option to reduce N_2O is already being implemented in other countries: reduction of N_2O emissions from adipic acid production by incineration or catalytic conversion. In the Netherlands no adipic acid is produced. All other options to technically reduce emissions of N_2O need further development, or at least some implementation time. The possibilities for implementation by 2000 of the different technologies are assessed.

The options considered have the potential to reduce total 1990 emissions of N_2O from the Netherlands by about 40%, if nothing else would change (Fig. 2). The technical potentials of these options to reduce N_2O emissions have been estimated for emissions from stationary combustion (15%), industry (70%), agriculture (35%) and waste (50%).

Most of the options formulated for agriculture are included in *National Environmental Policy Plan 2* (NMP-2). Additional measures in agriculture include improvement of fertilizer N efficieny, for instance by the use of slow-release fertilizers. Most of the reduction may be achieved by a catalytic reduction step in nitric acid production. Development of a catalytic converter seems feasible within a few years. However, the implementation of a such a catalytic converter may not be achieved by 2000.

Conceivable technologies that will not be implementable before 2000 include a number of promising options, such as low NOx engines in vehicles, electric vehicles, NOx reduction with low N_2O formation in stationary combustion and development of modified combustors.

Past and future N_2O emissions

Chapter 6 presents past emissions for N_2O and projections for the future. Global emissions of nitrous oxide are closely related to food production for the human population and will therefore increase along with population growth. The Dutch government has subscribed to a long-term international quiality target, calling for the *stabilization of greenhouse gas concentrations in CO_2-equivalents at a level well below doubling of the pre-industrial concentrations*, as described in a Dutch climate policy document (Memorandum on Climate Change). The N_2O contribution to global warming associated with this global aim can be limited to 4% if global anthropogenic emissions are reduced by 60 - 100% within 25 years.

The Dutch memorandum on climate change states that the Netherlands will make a reasonable contribution towards achieving abovementioned international objective. The Netherlands also signed the United Framework Convention on Climate Change, the ultimate objective of which is to achieve *a stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system; such a stabilization should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.* The developed country parties commit themselves specifically to demonstrate in their national policies that they are taking the lead in modifying longer-term trends in emissions.

In addition to above-mentioned general aim, the Dutch policy goal for N_2O has been formulated as a stabilization of Dutch emissions at their 1990 levels in 2000. In the Netherlands, emissions of N_2O have been increasing, reaching 37 Gg N y^{-1} (58 Gg N_2O y^{-1}) in 1990. The *current policies* projections result in an increase of N_2O emissions: by 2000, 2010, and 2015 the respective emissions are 1%, 6% and 10% higher than in 1990 based on method II. The calculated increase is the net effect of decreasing agricultural and "other" emissions, while emissons from energy, industry, and waste increase. In particular, emissions from transport increase as a result of the introduction of 3-way catalytic converters in cars. The estimated increase is low compared to the uncertainty in the total estimate. However, the largest uncertainties involve emission factors, not the activity data. This implies that the trends in N_2O emissions are relatively certain.

Implementation of *National Environmental Policy Plan 2* (NMP-2) is expected to prevent less than 1 Gg N_2O-N emissions from 2000 onwards. This is not sufficient for a stabilization at the 1990 level after 2000. The additional policy options could reduce next century's emissions by another 11 - 12 Gg N y^{-1}, so that 28 Gg N y^{-1} is emitted by 2015 (Fig. 2). The effect of additional policies is dominated by the catalytic N_2O reduction in nitric acid production which still has to be developed. Without this catalytic reduction step, a stabilization of Dutch N_2O emissions after the year 2000 would seem much more difficult. The Dutch emission in the additional policy projections is about 25% below the 1990 emission. To achieve a much further reduction, which could be needed to stabilize CO_2-equivalent concentrations at a level well below doubling of the pre-industrial concentrations, the development of yet unavailable or unknown technologies, or a reduction in the use of energy, mobility and the use of fertilizers is needed.

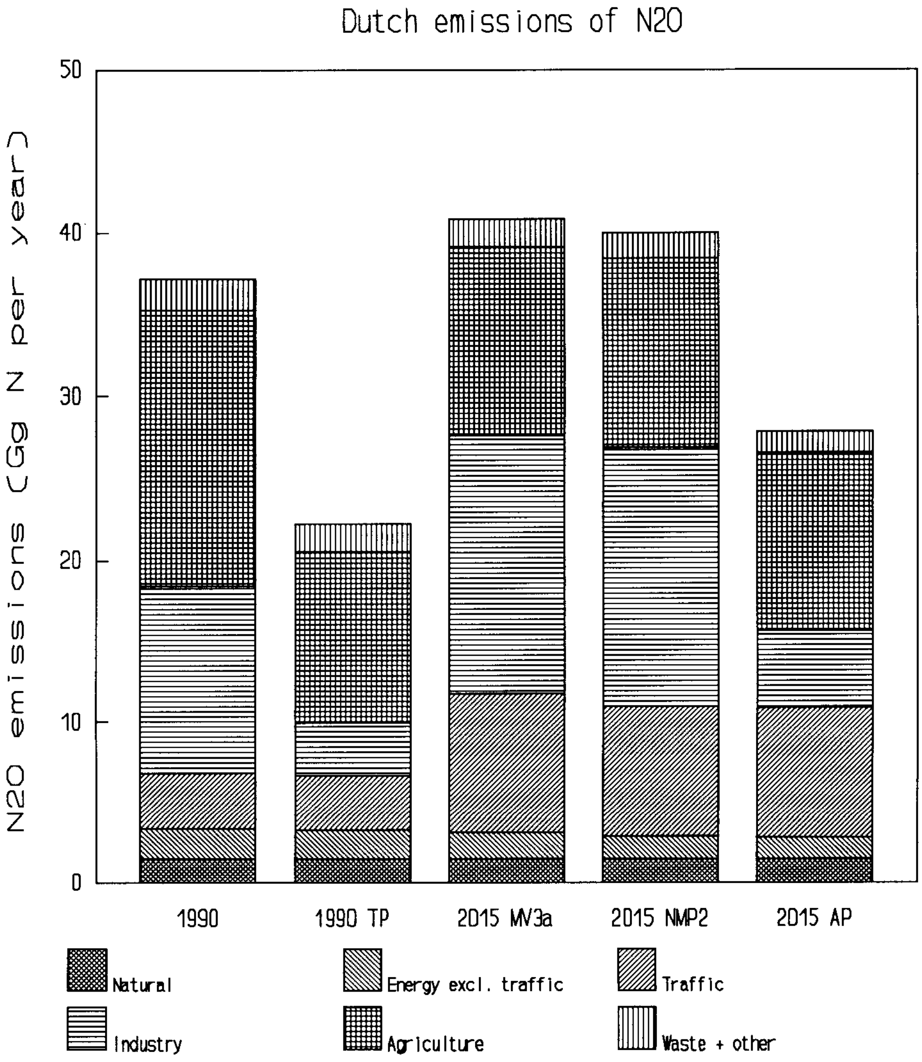


Fig. 2. Dutch 1990 emissions of N_2O (1990), emissions in 1990 minus the theoretical technical potential to reduce emissions (TP) (if nothing else would change), and the 2015 projections based on current policy (MV3a), *National Environmental Policy Plan 2* (NMP-2) and additional policy (AP).

Conclusions

The present study shows that despite a number of uncertainties, it is possible to explain the observed trend in atmospheric concentrations by known global sources. There are more uncertainties involved in estimating national than global emissions, because the global source strength can be deduced from atmospheric mass balances.

Despite the uncertainties involved, it is likely that without additional policy Dutch N_2O emissions will continue to increase in the future. Several environmental policy measures that have already been formulated for abatement of, for instance, acidification and eutrophication affect N_2O emissions. Some of these tend to increase N_2O emissions, while others may result in a reduction of N_2O emissions.

The technological options considered may reduce Dutch emissions by 25% relative to 1990, and include (1) a catalytic reduction step in nitric acid production, (2) improved fertilizer-N use efficiency by, for instance, the use of slow-release fertilizers, (3) improved combustion of municipal solid waste and sewage treatment, and (4) improved combustion in older power plants, and afterburning or catalytic reduction in fluidized bed combustion. The largest reduction can be achieved in nitric acid production, but the assumption that a catalytic converter can be implemented by 2000 may be optimistic.

The uncertainty in estimates on Dutch emissions could be reduced by (1) measurements of N_2O production during nitric acid production and other industrial sources in the Netherlands, (2) further investigation of N_2O production in vehicles, (3) monitoring of emissions from Dutch soils, including different types of agricultural soils and management types, (4) investigating N_2O production in Dutch groundwaters and surface waters, (5) investigation of atmospheric formation of N_2O and (6) the effect of global warming on N_2O emissions.

SAMENVATTING

Dit rapport geeft een een overzicht van de huidige kennis over lachgas (N_2O). Het beschrijft het gedrag van N_2O in de atmosfeer (hoofdstuk 2), wereldwijde bronnen en putten (hoofdstuk 3), Nederlandse emissie in 1990 (hoofdstuk 4), opties om emissies te reduceren (hoofdstuk 5) en projekties (hoofdstuk 6).

N_2O in de atmosfeer

Lachgas komt van nature voor in de atmosfeer van de aarde. De atmosferische concentratie is momenteel hoger dan gedurende de afgelopen 45000 jaar. De N_2O concentratie is sinds het begin van deze eeuw toegenomen, hoogstwaarschijnlijk als gevolg van menselijke aktiviteiten. De N_2O concentratie in de troposfeer vertoont weinig ruimtelijke variatie; dit wordt mede veroorzaakt door de lange atmosferische verblijftijd van ongeveer 120 jaar. De N_2O concentraties zijn op het noordelijk halfrond iets hoger dan op het zuidelijk.

Lachgas veroorzaakt 4 - 6% van de versterking van het broeikaseffekt. Het is een krachtig broeikasgas, met een *Global Warming Potential* van 170 - 270 (CO_2 = 1). Lachgas draagt ook bij aan de aantasting van de ozonlaag; in welke mate is echter onduidelijk.

Er vindt enige vorming van N_2O in de troposfeer plaats. In de literatuur zijn hiervoor zijn drie chemische mechanismen beschreven. Vorming in de troposfeer levert naar alle waarschijnlijkheid een bescheiden bijdrage aan atmosferisch N_2O. Lachgas is chemisch inert in de troposfeer, maar wordt afgebroken in de stratosfeer door met name ultraviolette straling.

Wereldwijde bronnen en putten

Hoofdstuk 3 beschrijft en kwantificeert wereldwijde bronnen en putten van N_2O. Er wordt in dit document onderscheid gemaakt tussen natuurlijke en antropogene bronnen en biogene en abiogene processen. Atmosferisch N_2O is voornamelijk van biologische oorsprong. Biogene vorming van N_2O vindt plaats in bodems en wateren tijdens nitrificatie en denitrificatie. Dit zijn biologische processen met N_2O als tussenprodukt. Biogene vorming van N_2O wordt door menselijk toedoen versterkt, in het bijzonder door stikstof toevoegingen aan bodems (kunstmest, dierlijke mest en atmosferische depositie). Abiogene vorming van N_2O vindt plaats tijdens bijvoorbeeld verbrandingsprocessen en in de atmosfeer. Het meeste abiogeen gevormde N_2O is het gevolg van menselijke aktiviteit zoals verbranding van fossiele brandstoffen en biomassa.

Uit de waargenomen toename in atmosferisch N_2O kan worden afgeleid dat de huidige wereldwijde emissie van N_2O 16.0 (11.9 - 19.1) Tg N y^{-1} bedraagt, waarvan 4.5 (3.9 - 5.1) Tg N y^{-1} antropogeen. Gepubliceerde inventarisaties komen uit op een totale emissie van 16.9 (9.6 - 27.6) Tg N y^{-1}, waarvan 6.1 (1.5 - 13.9) antropogeen. Het totaal van de inventarisaties komt dus overeen met het totaal gebaseerd op een massabalans van de atmosfeer. Enkele antropogene bronnen kunnen echter overschat zijn in de literatuur.

Antropogene bronnen van N_2O zijn energiegebruik (0.9 Tg N y^{-1}), industrie (0.5 Tg N y^{-1}), landbouw en veranderend landgebruik (2.9 Tg N y^{-1}), afval (1.0 Tg N y^{-1}) en overige bronnen (0.8 Tg N y^{-1}) (Fig. 1). Ongeveer 50% van de huidige wereldwijde antropogene N_2O emissie hangt samen met voedselproduktie voor mensen (inclusief veranderend landgebruik, industriële kunstmestproduktie en vorming van N_2O in met NH_3 vervuilde lucht).

Milieubeleid kan de uitstoot van N_2O op verschillende manieren indirect beinvloeden; het netto effekt is niet altijd op het eerste gezicht duidelijk: (1) reductie van de uitstoot van NOx en NH_3 leidt tot een afname in door atmosferische depositie geïnduceerde biogene emissies van N_2O, (2) technologieën om NOx te reduceren bij verbrandingsprocessen kunnen leiden tot verhoogde N_2O vorming, vooral bij de geregelde 3-weg katalysator in verkeer, (3) enkele technologieën om NH_3 emissies terug te dringen vergroten de N_2O uitstoot; voorbeelden zijn het injecteren van mest in plaats van oppervlakkig toedienen en het aanzuren van mest met salpeterzuur, (4) maatregelen die het gebruik van energie, kunstmest, etc. verminderen kunnen de hieraan gerelateerde N_2O uitstoot evenredig verminderen.

Nederlandse emissie in 1990: twee methoden

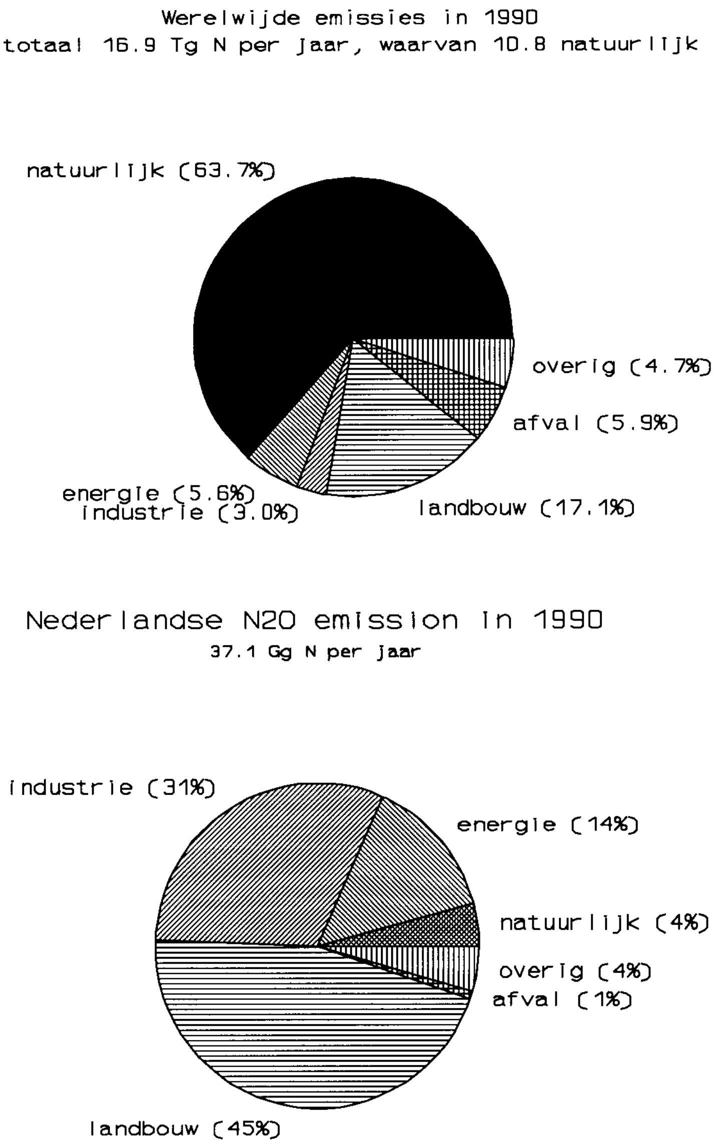
In hoofdstuk 4 worden twee methoden beschreven om nationale emissies van N_2O naar de atmosfeer te schatten. Beide methoden worden gebruikt om de Nederlandse emissie in 1990 te bepalen.

- De eerste methode (methode I) wordt door IPCC/OECD ontwikkeld. Volgens deze methode bedraagt de Nederlandse emissie in 1990 17 (6 - 38) Gg N y^{-1}, ofwel 27 (10 - 60) Gg N y^{-1}. Abiogene processen in industrie en transport leveren de belangrijkste bijdragen.
- De tweede methode (method II) betreft een bijgewerkte bestaande RIVM methode. Methode II resulteert in hogere emissies voor 1990 dan methode I: 37 (13 - 70) Gg N y^{-1}, ofwel 58 (20 - 110) Gg N_2O y^{-1}. Volgens method II levert landbouw de belangrijkste bijdrage aan de Nederlandse emissie.

Er zijn drie redenen om method II meer geschikter te achten dan methode I:

- Methode II omvat meer bronnen van N_2O is daarom completer dan methode I. De volgende bronnen ontbreken in methode I: N_2O emissies tengevolge van uitspoeling van stikstof uit bodems, andere stikstoflozingen op oppervlaktewater, rioolwaterzuivering, atmosferische depositie van NOx, atmosferische depositie van NH_3 dat niet uit de landbouw afkomstig is, mest in stallen, vorming in de atmosfeer en het gebruik als verdovingsmiddel. Methode II tracht alle bekende bronnen van N_2O te schatten,
- De emissiefaktoren die gebruikt worden in methode II zijn voor een deel gebaseerd op Nederlands onderzoek en daarom wellicht beter van toepassing op de Nederlandse situatie.
- Methode I geeft een onderschatting van de wereldwijde emissies. Dit komt waarschijnlijk doordat methode I niet alle bronnen van N_2O omvat en relatief lage emissiefaktoren gebruikt.

Volgens methode II is tenminste 95% van de Nederlandse emissie in 1990 antropogeen. Belangrijke bronnen zijn landbouw (45%), industrie (31%) en transport (10%). De emissie uit landbouw is voornamelijk afkomstig van bodems (86%). Oppervlaktewater (uitspoeling) en stallen dragen 11%, respektievelijk 3% bij.



Werelwijde emissies in 1990
totaal 16.9 Tg N per jaar, waarvan 10.8 natuurlijk

Nederlandse N2O emission in 1990
37.1 Gg N per jaar

Fig. 1. Wereldwijde en Nederlandse emissie van N_2O in 1990. De Nederlandse emissie is volgens methode II.

Reductie van antropogene N_2O emissies

Hoofdstuk 5 beschrijft opties om N_2O emissies te reduceren. Het technisch potentieel van een aantal opties is geschat. Het economisch potentieel is niet in beschouwing genomen. Opties om de volumes van aktiviteiten te reduceren zijn slechts kwalitatief beschreven. Momenteel zijn er in het Nederlandse beleid geen specifieke N_2O maatregelen geformuleerd.

Er wordt buiten Nederland één techniek toegepast om de uitstoot van N_2O te verminderen: N_2O gevormd tijdens adipinezuurproduktie wordt verbrandt of katalytisch gereduceerd. In Nederland wordt geen adipine geproduceerd. Alle andere opties om N_2O

emissies te doen afnemen vereisen onderzoek, of tenminste enige implementatietijd. De mogelijkheden om technologieën nog voor de eeuwwisseling te implementeren zijn onderzocht.

Het technisch potentieel van de beschreven opties om de totale Nederlandse N_2O uitstoot in 1990 te reduceren bedraagt 40%, wanneer er daarnaast niets zou veranderen (Fig. 2). Het technisch potentieel van opties om N_2O emissies te reduceren is geschat voor emissies van stationaire verbranding (15%), industrie (70%), landbouw (35%) en afval (50%). De meeste opties voor landbouw zijn opgenomen in het nationale milieubeleidsplan 2 (NMP-2). Additionele maatregelen in de landbouw betreffen efficiënter gebruik van stikstof, bijvoorbeeld door gebruik van zogenaamde *slow-release fertilizers*. De grootste reductie kan bereikt worden in de industrie, door een katalytische reductie van N_2O bij salpeterzuurproduktie. Technische ontwikkeling van een dergelijk kalalysator lijkt mogelijk binnen enkele jaren. Het is echter niet zeker of implementatie ervan voor 2000 te realiseren is.

Enkele veelbelovende technieken, al dan niet in ontwikkeling, zijn niet voor 2000 implementeren. Voorbeelden hiervan zijn motoren met lage NOx uitstoot voor voertuigen, elektrische voertuigen, NOx reductie technieken voor stationaire verbranding waarbij weinig N_2O wordt gevormd en verbeterde branders.

Scenario's voor N_2O emissies

In hoofdstuk 6 worden emissies van N_2O in verleden en toekomst gepresenteerd. Wereldwijde emissies van lachgas hangen nauw samen met voedselproduktie voor mensen. Wereldwijde emissies nemen daardoor toe met de groeiende werelbevolking. Het Nederlandse beleid is gericht op *stabilisatie van de concentraties van broeikasgassen in de atmosfeer vóór het einde van de volgende eeuw op een nivo ruim beneden een verdubbeling van de pré-industriële concentraties* (Nota Klimaatverandering). Realisatie van dit doel leidt naar verwachting tot een mondiaal gemiddelde temperatuurstijging van 0.1 °C per decade. Wanneer de wereldwijde antropogene N_2O emissie binnen 25 jaar wordt gereduceerd met 60 - 100% kan de bijdrage van N_2O aan deze opwarming beperkt blijven tot 4%.

In de Nota Klimaatverandering wordt tevens vermeld dat Nederland een redelijke bijdrage zal leveren aan het bereiken van bovengenoemde internationale doelstelling. Nederland heeft tevens het internationale klimaatverdrag ondertekend, waarin het uiteindelijke doel is geformuleerd als *stabilisatie van de broekasgas concentraties op een nivo dat gevaarlijke menselijke verstoring van het klimaat zou voorkomen; deze stabilisatie moet bereik worden binnen een zodanig tijdsbestek dat ecosystemen zich op een natuurlijke wijze kunnen aanpassen aan klimaatverandering, dat de voedselproduktie niet bedreigd wordt en dat de economie zich op duurzame wijze kan ontwikkelen.* Industrielanden verplichten zich om met nationaal beleid te demonstreren dat ze het voortouw nemen om een breuk in de emissietrend te bewerkstelligen.

Voor de korte termijn streeft het Nederlandse beleid naar een stabilisatie van de Nederlandse N_2O emissie op het nivo van 1990 in het jaar 2000. De Nederlandse uitstoot van N_2O is gestegen tot 37 Gg N y^{-1} (58 Gg N_2O y^{-1}) in 1990. In de projekties gebaseerd op huidig beleid nemen de N_2O emissie toe. In 2000, 2010 en 2015 kan de Nederlandse uitstoot 1%, 6%, respektievelijk 10% hoger zijn dan in 1990 (geschat met methode II). De berekende toename is het netto effekt van afnemende N_2O emissies uit de landbouw en uit de categorie "overig", terwijl de N_2O uitstoot uit energie, industrie en afval toenemen. Met name de uitstoot van N_2O door verkeer neemt toe tengevolge van de introduktie van de geregelde 3-weg katalysator in auto's. De geschatte toename is klein vergeleken met de onzekerheden in de totale schatting. De grootste onzekerheid betreft echter de emissiefaktoren, niet de volumes van aktiviteiten. Dit betekent dat de trends in N_2O emissies relatief zeker zijn.

Door implementatie van het nationale milieubeleidsplan 2 (NMP-2) kan naar verwachting een jaarlijke uitstoot van 1 Gg N_2O-N vermeden worden vanaf 2000. Additionele maatregelen kunnen in de volgende eeuw de jaarlijkse uitoot met 11 - 12 Gg N extra reduceren, zodat de emissie in 2015 is gereduceerd tot 28 Gg N y^{-1} (Fig. 2). Het effekt van additionele maatregelen wordt gedomineerd door katalytische N_2O reductie bij de industriële produktie van salpeterzuur. Een dergelijke katalysator kan ontwikkeld worden. Stabilisatie van de Nederlandse N_2O emissie wordt na 2000 veel moeilijker zonder deze katalytische reductie. In de *additional policy* projekties is de Nederlandse uitstoot ongeveer 25% lager dan in 1990. Een verdere reductie zou nodig kunnen zijn om de CO_2-equivalente concentratie van broeikasgassen te stabiliseren op een nivo ruim beneden een verdubbeling van de pré-industriële concentraties. Het realiseren van een verdere reductie vereist ontwikkeling van nu nog niet beschikbare of niet bekende technologie, of reductie in het gebruik van energie, mobiliteit en gebruik van meststoffen.

Conclusies

Ondanks een aantal onzekerheden is het mogelijk gebleken de waargenomen trend in atmosferisch N_2O te verklaren met bekende bronnen. Schattingen van mondiale emissies zijn minder onzeker dan die van nationale, omdat de wereldwijde emissie afgeleid kan worden van een massabalans van de atmosfeer.

Ondanks de onzekerheden is het waarschijnlijk dat zonder specifiek beleid de Nederlandse N_2O emissie zal blijven stijgen in de toekomst. Verschillende bestaande beleidsmaatregelen beïnvloeden de uitstoot van N_2O, bijvoorbeeld die ter bestrijding van verzuring en vermesting. Een aantal van deze maatregelen kan de N_2O uitstoot doen toenemen, terwijl andere kunnen resulteren in een reductie van de N_2O emissie.

De in hoofdstuk 5 beschreven technische opties kunnen de Nederlandse uitstoot met 25% reduceren ten opzichte van 1990 door onder anderen (1) katalytische N_2O reductie bij de industriële produktie van salpeterzuur, (2) efficiënter gebruik van stikstof meststoffen, bijvoorbeeld door gebruik van *slow-release fertilizers*, (3) aanpassingen in de verbranding van afval, en (4) optimalisatie van de verbranding van fossiele brandstoffen, met name in oudere centrales en katalytische N_2O reductie in werveldbedverbranding. De grootste reductie kan worden gerealiseerd bij salpeterzuurproduktie. De aanname dat een katalysator geïmplementeerd kan worden in 2000 zou echter optimistisch kunnen zijn.

De onzekerheden in schattingen van de Nederlandse N_2O emissie zouden verminderd kunnen worden door (1) meten van N_2O vorming tijdens produktie van salpeterzuur en andere industriële processen in Nederland, (2) voortzetting van onderzoek naar N_2O produktie door voertuigen, (3) meten van N_2O produktie in Nederlandse bodems, waaronder verschillende agrarische bodem- en bedrijfstypen, (4) onderzoek naar N_2O produktie in grondwater en oppervlaktewater in Nederland, (5) onderzoek naar de vorming van N_2O in de atmosfeer en (6) onderzoek naar de effekten van klimaatverandering op N_2O emissies.

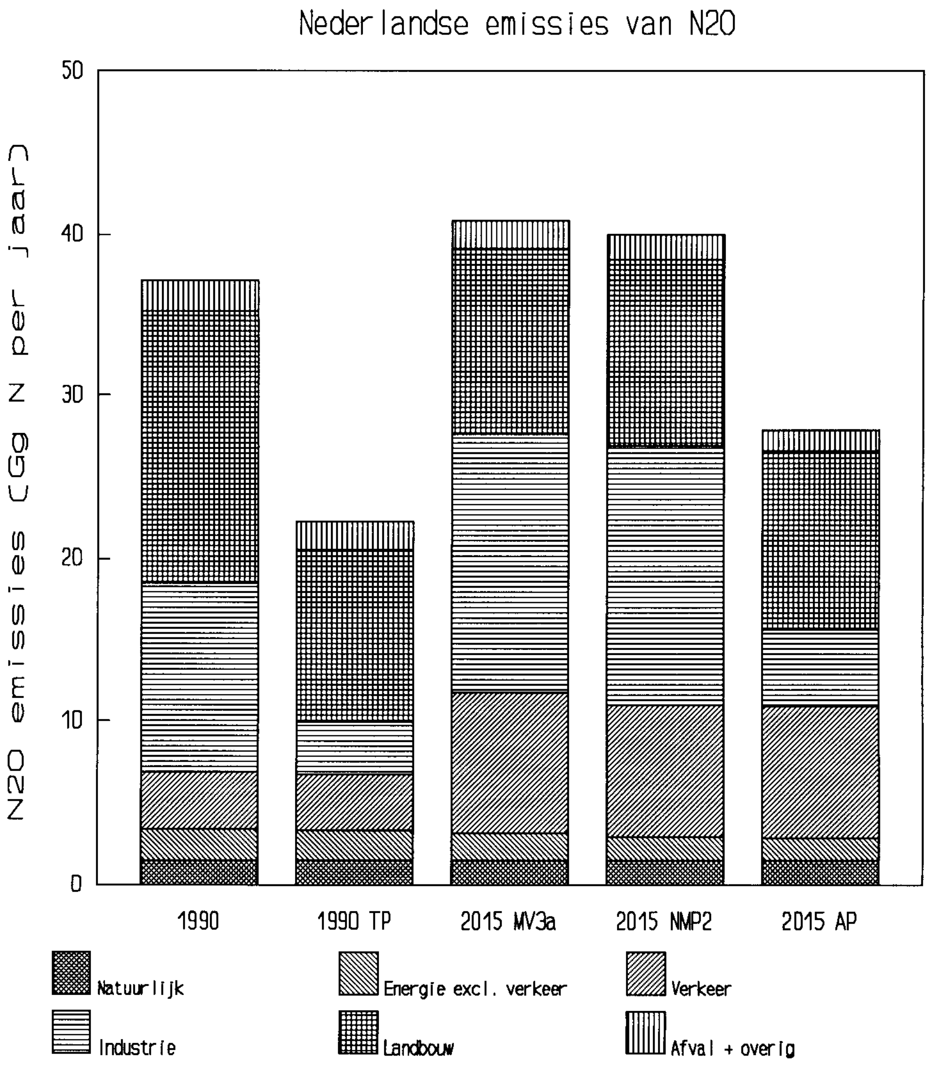


Fig. 2. Nederlandse emissie van N_2O in 1990 (1990), de emissies in 1990 minus het theoretisch technisch potentieel om emissies te reduceren (TP) (als verder niets zou veranderen) en de projekties voor 2015 gebaseerd op huidig beleid (MV3a), het nationale milieubeleidsplan 2 (NMP-2) en additioneel beleid (AP).

1 INTRODUCTION

Concentrations of nitrous oxide (N_2O), one of the natural components of the earth's atmosphere, have been increasing due to human activities. Rising N_2O concentrations are of environmental concern for at least two reasons: (1) N_2O contributes to the greenhouse effect and (2) N_2O plays a role in stratospheric ozone depletion.

Nitrous oxide is one of the gases that contribute to the natural greenhouse effect. Due to greenhouse gases the earth's atmosphere lets a relatively large amount of shortwave (solar) radiation in, but does not let longwave surface radiation out so well. As a result, the natural temperature of the earth is about 33 °C warmer than would be expected from incoming solar radiation. An increase in greenhouse gas concentrations enhances the natural greenhouse effect, which could lead to a temperature increase. There is little doubt that ongoing perturbation of the climate system will ultimately result in global warming and associated climate change.

Nitrous oxide is also one of the chemically active gases in the stratosphere, being the most important source of stratospheric NO. Thus changes in concentrations of N_2O may alter stratospheric chemistry, which in turn may affect stratospheric ozone depletion.

Knowledge on anthropogenic N_2O emissions is increasing. Up until 1987, it was believed that fossil fuel combustion was the main source of anthropogenic N_2O. However, this appeared to be incorrect. The present view is that several relatively small sources are the reason for N_2O concentrations increasing.

Although it has been long known that an increase in atmospheric N_2O may have adverse environmental effects, negligible effort has so far been put into reducing N_2O emissions. There are no international agreements to reduce this emission. The Netherlands is one of the few countries that included N_2O emissions in their national policy, aimed at stabilizing N_2O emissions at the 1990 level. However, no specific N_2O measures have been taken yet to achieve this goal.

The purpose of this study is to review current knowledge on N_2O emissions. In this report, first the atmospheric behavior of N_2O is reviewed (chapter 2). Second, an overview is given of N_2O sources and sinks, both in pre-industrial times and at present (chapter 3). Next, Dutch 1990 emissions are estimated using two methods (chapter 4). After investigation of the possibilities to reduce N_2O emissions (chapter 5), Dutch N_2O emissions are presented for the period 1980 - 2015, and emission targets discussed (chapter 6). In chapter 7 major conclusions are drawn.

In chapter 4 two method for estimating country emissions of N_2O are compared[1]. Method I is a method in development by IPCC/OECD (1994). Method II is an update of the method used in *National Environmental Outlook 3*. Thus the emissions presented here differ from those in National Environmental Outlook 3 (RIVM, 1993a) and therefore also from those reported in two other recent reports on Dutch emissions, the "emissie jaar rapport" (Berkowski et al., 1994) and the background document for the National Communication for the Climate Convention (Van Amstel et al., 1994). The differences are listed in Appendix 4-2.

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[1] Throughout this report, N_2O emissions are reported in g N per year; 1 g N_2O = 28/44 g N.

2 N_2O IN THE ATMOSPHERE

2.1 Introduction

Nitrous oxide (N_2O) is one of the natural components of the earth's atmosphere. This chapter describes the observed increase in atmospheric N_2O (2.2), its radiative properties (2.3), and relevant chemical processes in the troposphere (2.4) and stratosphere (2.5).

2.2 Atmospheric concentrations

The atmospheric N_2O concentrations have been relatively constant: within the range of 280 - 290 parts per billion of volume (ppbv) for many centuries (Weiss, 1981b; Pearman et al., 1986; Brasseur and De Rudder, 1987; Wigley, 1987; Khalil and Rasmussen, 1988). For instance, between 150 and 3000 years ago, the average concentration was 285 $\pm$ 1 ppbv (Khalil and Rasmussen, 1988). This has been determined by analysis of ancient air trapped in polar ice. There have also been periods during which concentrations of N_2O were less constant. Especially during the last glacial maximum (about 25,000 years ago) concentrations of N_2O were about 30% lower than during the Holocene epoch (Leuenberger and Siegenthaler, 1992). Similarly, N_2O concentrations decreased by a few percent during the little Ice age, between 1450 and 1750 AD (Khalil and Rasmussen, 1989). These findings suggest a temperature dependency of atmospheric N_2O.

The present-day N_2O atmospheric concentration, 310 ppbv, exceeds the concentration in 45,000 years (Leuenberger and Siegenthaler, 1992). Atmospheric N_2O, measured systematically since the mid-seventies, is found to be still increasing at a rate of 0.2 - 0.3% per year.

At present two monitoring networks measure atmospheric N_2O: the Geophysical Monitoring on Climate Change of NOAA (GMCC) and the Atmospheric Lifetime Experiment, or Global Atmospheric Gases Experiments (ALE-GAGE, Fig. 2-1). In both GMCC and ALE-GAGE, N_2O concentrations were measured at five ground-based stations for more than 10 years. The observed increase between 1978 and 1988 was 0.72 (0.63 - 0.75) ppbv y^{-1}, or 3.6 Tg N y^{-1} in GMCC (Bodhaine and Rosson, 1988), and 0.91 ± 0.3 ppbv y^{-1}, or 4.55 ± 0.15 Tg N y^{-1} in ALE-GAGE (Prinn et al., 1990). Rasmussen and Khalil (1986) concluded from 10 years of measurements that the N_2O concentration increased at a rate of 1.04 ± 0.4 ppbv y^{-1} between 1975 and 1985. However, their estimate is based on January measurements from two stations only. Khalil and Rasmussen (1992) reported a 0.80 ± 0.02 ppbv annual increase between 1977 and 1988.

The anthropogenic increase in atmospheric N_2O started this century. There are indications that during the first half of the century N_2O increased only moderately, while during the second half the growth rate has increased (Khalil and Rasmussen, 1988; 1992). Similarly, in recent years N_2O may have increased about 0.2 ± 0.1 ppbv y^{-1} faster than during the mid-seventies (Khalil and Rasmussen, 1992).

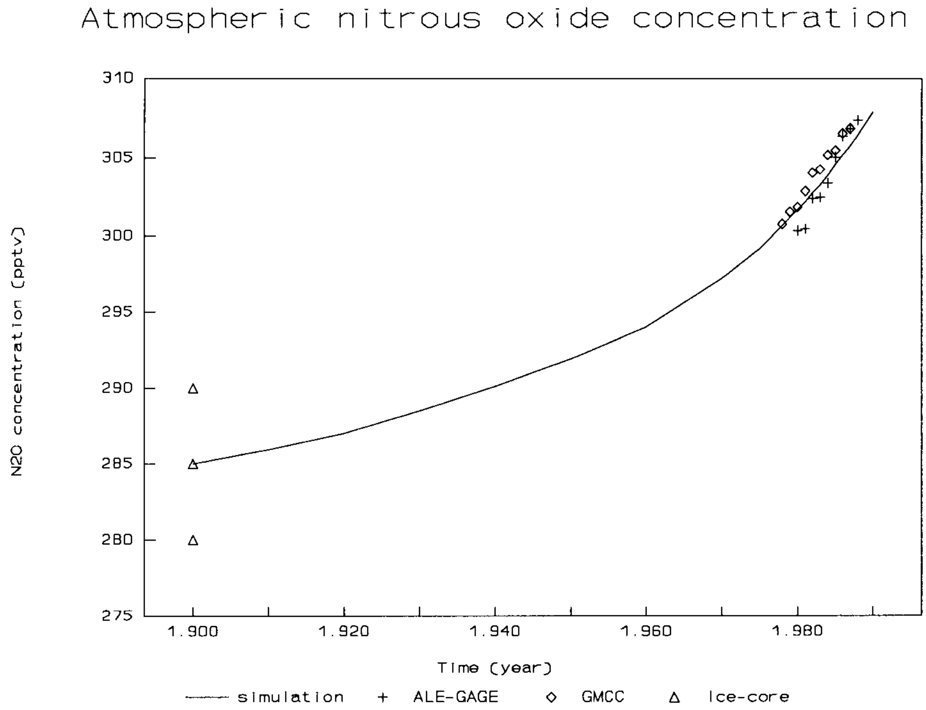


Fig. 2-1. Atmospheric concentrations observed in the ALE-GAGE and GMCC monitoring network and measured in ancient air trapped in polar ice. The solid line shows a possible increase.

North-South concentration gradient

Spatial variation in atmospheric concentrations of gases is the net result of spatial differences in sources and sinks and atmospheric transport. Sources and sinks of N_2O are widely distributed over the earth, and the atmospheric lifetime of N_2O (about 120 years) is long if compared to the tropospheric mixing time (a few years). As a result, concentrations of N_2O are relatively homogeneously distributed over the troposphere.

In the present troposphere a moderate interhemispheric difference in atmospheric N_2O is observed. Northern hemisphere concentrations exceed those of the southern hemisphere by about 1 ppbv (Weiss, 1981a/b; Delory et al., 1988; Khalil and Rasmussen, 1988; Butler et al., 1989; Prinn et al., 1990). This is most probably caused by an interhemispheric difference in present emissions.

In the pre-industrial atmosphere the interhemispheric difference may have been different than observed today. Some studies suggest either no, or a reversed interhemispheric difference in pre-industrial N_2O concentrations. This may suggest that non-anthropogenic sources of N_2O are located mainly in the southern hemisphere (Weiss et al., 1981a/b; Levy et al., 1982; Khalil and Rasmussen et al., 1988).

In the stratosphere, where atmospheric N_2O is broken down, concentrations of N_2O

decrease with height to almost negligible levels at 30 km altitude (Fabian et al., 1981).

Seasonal cycle

A seasonal cycle in atmospheric N_2O can be expected, since its source is largely biogenic. Biological processes, and thus most N_2O emissions, are known to be sensitive to climatic variables such as temperature and precipitation. Indeed, Khalil and Rasmussen (1983) reported seasonally changing N_2O concentrations from three years of ALE-GAGE data. However, no seasonal cycle could be concluded from 10 years of GMCC data (Prinn et al., 1990). Matthias et al. (1979) found a diurnal variation at ground surface, decreasing with height. More recently, Khalil and Rasmussen (1992) concluded that since 1977 atmospheric N_2O concentrations have shown a quasi-triannual cycle. These reported variations are small, and disagree qualitatively. Clearly, seasonal variations in N_2O concentrations are not as obvious as those of, for instance, CO_2 and CH_4. Some authors even doubt whether seasonal cycles for N_2O exist at all (for instance, Duxbury et al., 1993).

2.3 N_2O and the greenhouse effect

Direct radiative forcing

Nitrous oxide is one of the "greenhouse gases" contributing to the so-called "greenhouse effect". The greenhouse effect is caused by a relatively strong absorption of outgoing long-wave radiation. Carbon dioxide, water vapour, methane and nitrous oxide are the most important natural greenhouse gases. Without the natural greenhouse effect the temperature of the earth would be about 33 °C lower than it is today (Houghton et al., 1990). An increase in atmospheric concentrations of greenhouse gases creates radiative forcing, perturbing the energy balance of the atmosphere. Anthropogenic emissions of greenhouse gases may thus enhance the greenhouse effect. The natural greenhouse effect is now well understood. Although many uncertainties still exist, there is little doubt that ongoing perturbation of the radiative balance will ultimately result in global warming (Houghton et al., 1990; 1992).

Atmospheric concentrations of greenhouse gases have been increasing considerably since pre-industrial times due to human activities. Relative to the year 1900, about 2 W/m^2 extra infrared radiation (radiative forcing) is absorbed by such greenhouse gases as CO_2, CH_4, halocarbons, and N_2O (Houghton et al., 1990). Radiative forcing by N_2O can be estimated as follows (Houghton et al., 1990; Wigley, 1987):

$$Q_t = B\ (\sqrt{C_t} - \sqrt{C_0})$$

where

t = time (year of calculation)

Q_t = radiative forcing due to N_2O at time t relative to time 0 ($W\ m^{-2}$)

B = $0.105\ W\ m^{-2}\ ppbv^{-0.5}$

C_t = atmospheric concentration at time t (ppbv)

C_0 = atmospheric concentration at time 0 (ppbv)

Assuming that atmospheric concentrations of N_2O have increased from 285 ppbv in pre-industrial times to 310 ppbv at present, the present radiative forcing by N_2O amounts to 0.08 W/m^2, or about 4% of the total forcing relative to pre-industrial times. The N_2O contribution to the enhancement of the greenhouse effect during the 1980s has been estimated at 6% (Houghton et al., 1990).

On a molecular and mass basis, N_2O is a much stronger greenhouse gas than CO_2 (Table 2-1). The direct radiative forcing per unit molecule change, and per unit mass change in the atmosphere for present-day concentrations are 206 times higher for N_2O than for CO_2 (Table 2-1). Moreover, N_2O has a relatively long atmospheric lifetime, so that once emitted, a molecule of N_2O contributes to the greenhouse effect longer than most other greenhouse gases do. The combined effect of both molecular and lifetime differences are reflected by the Global Warming Potential (GWP) of gases. The GWP of greenhouse gases has been defined by IPCC as the time-integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg of carbon dioxide. Although GWPs of greenhouse gases are not easily determined, they can be regarded as an indication of the relative potential of gases to alter the earth's climate.

Indirect radiative forcing

The radiative effects discussed so far concern only the direct absorption of infrared radiation by the compounds studied. Next to these direct effects, greenhouse gases may cause indirect radiative forcing, resulting after chemical interactions in the atmosphere.

For N_2O the indirect radiative forcing is uncertain (Table 2-1). In the troposphere N_2O can be considered chemically inert, causing no indirect radiative forcing. In the stratosphere N_2O is an important source of NO, one of the compounds playing a role in stratospheric ozone depletion. At present, it is unclear to what extent N_2O contributes to the deterioration of the ozone layer. Moreover, it is not certain how stratospheric ozone destruction and global warming affect each other. Several mutual processes have been proposed: (i) stratospheric ozone depletion may slow down global warming, as suggested in some calculations, because a decrease in stratospheric ozone may cool the lower stratosphere (Ramaswamy et al., 1992); (ii) an increase of ultraviolet radiation as result of stratospheric ozone depletion may affect the photochemistry of the troposphere, and thus concentrations of tropospheric ozone (Thompson, 1991); (iii) not only halocarbons and N_2O, but also emissions of CH_4 and CO_2 may influence stratospheric ozone levels (Brasseur and Hitchman, 1988); (iv) enhancement of the greenhouse effect may result in stratospheric cooling, as a result of which halocarbons and possibly N_2O may become more effective ozone destroyers (Austin et al., 1992). At present it is not clear which of the above processes, or other yet unidentified effects, is dominant on a global scale. However, it is most probable that the N_2O contribution to stratospheric ozone depletion, and its indirect radiative effect on the earth's surface temperature, is relatively small (Houghton et al., 1992).

Table 2-1. The direct radiative effects of N_2O and CH_4 relative to that of CO_2 and the sign of the indirect radiative effects (Houghton et al., 1990; 1992)

	dQ/dC molec.[1]	dQ/dC mass[1]	GWP[2] 20 year	GWP[2] 100 year	GWP[2] 500 year	Indirect effects
CO_2	1	1	1	1	1	none
CH_4	21	58	35	11	4	positive
N_2O	206	206	260	270	170	uncertain

[1] dQ/dC = radiative forcing relative to CO_2 per unit molecule change (molec.) or per unit mass change (mass) in the atmosphere for present day concentrations; [2] GWP = Global Warming Potential = the time-integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg of carbon dioxide, over 20, 100 and 500 years

2.4 Tropospheric chemistry

Once in the troposphere, nitrous oxide is chemically inert. Some N_2O formation in the troposphere may, however, occur. Three mechanisms of N_2O production have been proposed in the literature: (i) formation in the gas phase (ii) via heterogeneous chemistry, and (iii) in discharge excited air.

(i) Formation of N_2O by oxidation of NH_3 (in the gas phase)

N_2O may be formed as a result of oxidation of NH_3. Most of the NH_3 emitted into the atmosphere reacts with sulphate aerosols. However, Dentener (1993) calculated that, worldwide, about 4% of atmospheric ammonia is oxidized by hydroxyl radicals (OH):

$$NH_3 + OH \rightarrow NH_2 + H_2O \qquad [1]$$

At NO_2 concentrations > 300 ppt most of the NH_2 reacts with NO_2 (reaction [2]). The efficiency of N_2O production is strongly dependent on concentrations of atmospheric O_3 and NO_2. When ambient NO_2 concentrations are less than 300 ppt, over 70% of NH_2 is oxidized by O_3:

$$NH_2 + NO_2 \rightarrow N_2O + H_2O \qquad [2]$$

$$NH_2 + O_3 \rightarrow NH_2O + O_2\text{, other products} \qquad [3]$$

Globally, the N_2O-N produced equals 1.3% of the NH_3-N emitted (Dentener, 1993). This process is most abundant in the tropics. In the grid cell covering the Netherlands, only 0.01% of the NH_3-N is calculated to be converted to N_2O (Dentener, pers.comm.).

(ii) Formation of N_2O in air containing NH_3 (heterogeneously)

An alternative mechanism for N_2O formation in air containing NO_3, NH_3, and O_3, has been proposed by Adema et al. (1990), who observed N_2O formation in experimental conditions. The experiments were carried out in a night-time system and under relatively dry conditions (about 15 ppmv H_2O). According to Adema et al. (1990), N_2O was most probably formed through the heterogeneous reaction of N_2O_5 and absorbed NH_3 at the wall of the reaction vessel (reaction [4]).

$NH_3 + N_2O_5 \rightarrow N_2O + HNO_3 + H_2O$ [4]

At high water concentrations (relative humidity > 75%) no N_2O formation was observed. This was possibly caused by displacement of adsorbed NH_3 by H_2O. N_2O formation via this mechanism could occur in ambient air. However, the significance of N_2O production in the atmosphere is thought to depend on the adsorption of H_2O and NH_3 to a surface in ambient polluted air. To what extent this reaction occurred in the unpolluted pre-industrial atmosphere is questionable.

(iii) Formation of N_2O from discharge-excited species

A third proposed mechanism for tropospheric N_2O production is formation of N_2O from excited gases. In experimental conditions, N_2O formation was observed in mixtures of N_2 and O_2 after discharges or irradiation. According to Fraser et al. (1990) interaction of discharge-excited N_2^* and O_2^* is the main N_2O-forming process (reaction [5]). However, the exact meachnism is still a matter of discussion.

$N_2^* + O_2^* \rightarrow N_2O + O$ [5]

In ambient air excited N_2^* and O_2^* could be formed during lightning, cloud discharges, coronal discharges, around high-voltage transmission lines and possibly in the stratosphere by radiation. Fraser et al. (1990) conclude that if reaction [5] is the main mechanism, its importance in natural atmospheric processes is limited.

2.5 Stratospheric chemistry

In the stratosphere about 90% of the N_2O is photolyzed (reaction [6]). About 10% is oxidized by $O(^1D)$ (reactions [7,8]), of which more than half to NO. This may diffuse, or settle out gravitationally to the earth's surface as HNO_3 (Donner and Ramanathan, 1980; NASA, 1992).

photolysis:

$N_2O + h\nu \rightarrow N_2 + O(^1D)$ [6]

oxidation:

$N_2O + O(^1D) \rightarrow N_2 + O_2$ (42%) [7]

$N_2O + O(^1D) \rightarrow NO + NO$ (58%) [8]

The NOx produced by reaction [8] allows the catalytic destruction of stratospheric ozone to be initiated. N_2O is the main source of NOx in the stratosphere, and therefore an important natural regulator of stratospheric ozone. An increase in N_2O most probably affects stratospheric ozone concentrations. It is not clear to what extent increased levels of atmospheric N_2O contribute to the present deterioration of the ozone layer. However, it seems likely that its contribution is minor if compared to that of chlorofluorocarbons (CFCs) and halons.

2.6 Conclusions

The atmospheric concentration of N_2O have been increasing during the last century. This is most probably the result of human activities. Atmospheric concentrations of N_2O are relatively constant throughout the troposphere; this is in line with its long atmospheric lifetime of about 120 years. Concentrations in the northern hemisphere are slightly higher than in the southern hemisphere.

Nitrous oxide is one of the natural greenhouse gases, with a Global Warming Potential of 170 - 270 (CO_2 = 1). About 4-6% of the present radiative forcing is caused by N_2O. It also contributes to stratospheric ozone depletion, however to what extent is not clear.

Nitrous oxide is chemically inactive in the troposphere, although some N_2O formation may occur. Three chemical pathways resulting in N_2O formation have been proposed in the literature. Their contribution to atmospheric N_2O is probably small. N_2O is broken down in the stratosphere, mainly by ultraviolet radiation.

3 GLOBAL SOURCES AND SINKS

3.1 Introduction

Nitrous oxide emissions result from a variety of sources. A distinction is made between biogenic and abiogenic, and between natural and anthropogenic sources (Table 3-1). *Biogenic* emissions are the result of biological processes. All other emissions are *abiogenic*. Emissions induced by human activities are considered *anthropogenic*, and all other emissions are *natural*. Biogenic N_2O production by nitrification and denitrification may be enhanced by human activities. This could result from:

- *Anthropogenic nitrogen input.* Nitrogen input to soils result from synthetic nitrogen fertilizers, animal manure, biological N fixation and atmospheric deposition of NOx and NHx. Nitrogen input to waters result from soil leaching, atmospheric deposition, and direct nitrogen inputs to surface waters from, for instance, industries. Nitrogen removal in sewage treatment plants is also regarded as an increased nitrogen availability to bacteria.
- *Loss of soil nitrogen.* Land clearing may increase soil decomposition and mineralization rates. The N mineralized may be nitrified and denitrified leading to N_2O and N_2 losses. Similar losses of soil nitrogen may occur after lowering of the groundwater table in wetlands.
- *Increase in microbial activity.* An increase in the earth's surface temperature could result in enhanced N_2O emissions caused by enhanced microbial acivity. In addition, the amount of N_2O produced during bacterial activity may change.

Most anthropogenic sources were grouped according to the method recommended by IPCC/OECD (1994). One exception to IPCC/OECD (1994) is biomass burning. All emissions of N_2O from biomass burning are considered agricultural emissions in contrast to the method of IPCC/OECD where part of biomass burning emissions are attributed to land use change. For some sources of N_2O, categorization is subjective since (biogenic) emissions are not always easily attributed to a certain activity. For example, changes in land use are not always for agricultural purposes. Atmospheric formation of N_2O in polluted air is partly due to agricultural activities (NH_3 pollution) and partly to energy use and industry (NOx pollution). And the N_2O emission as a result of nitrogen leaching may be the result of agricultural, energy related, or industrial nitrogen input. Thus the following sources are distinguished (Table 3-1):

- *Natural emissions.* Natural emissions of N_2O are mainly the result of biogenic processes in soils and aquatic systems, where nitrifying and denitrifying bacteria produce N_2O. Natural abiogenic sources of N_2O are its formation in the unpolluted troposphere and emissions during natural fires.
- *Energy.* Energy use includes stationary and mobile combustion of fossil fuels and fuelwood. The N_2O emissions result from (i) N_2O formation during combustion, (ii) enhancement of biogenic N_2O emissions after deposition of NOx on soils and oceans, (iii) N_2O formation due to discharges around high-voltage transmission lines, and (iv) formation in NOx polluted air. The last source is included in the

category "other".

- *Industry.* Known industrial sources of N_2O are production of adipic acid (non-existing in the Netherlands) and nitric acid. Direct input or atmospheric deposition of industrial nitrogen enhances biogenic production of N_2O in soils and surface waters (in category "other").
- *Agriculture and land use change.* Agricultural activities are a major source of anthropogenic N_2O. Agricultural N_2O emissions include (i) soil emissions induced by fertilizers, manure, biological N_2 fixation or atmospheric deposition of NH_3; (ii) aquatic emissions after nitrogen leaching or run-off; and (iii) direct and post-burn emissions caused by biomass burning. Conversion of tropical forests to agricultural land is mostly done by clearing the forests by burning, during which N_2O is formed. After clearing, biogenic emissions of N_2O can be enhanced for years as a result of increased mineralization. Two other sources of N_2O related to agricultural activities are included in other categories: (iv) the category "industry" includes emissions during the industrial production of nitric acid, which is used mainly for synthetic nitrogen fertilizers, and (v) the category "other" includes atmospheric formation from NH_3, mainly from manure.
- *Waste.* Waste includes biological treatment of sewage water, and municipal solid waste (MSW) incineration.
- *Other.* The category "other" includes extra N_2O emissions as a result of global warming, non-agricultural N loading to surface waters, atmospheric deposition of non-agricultural NH_3 and non-energy NOx, atmospheric formation in NOx and NH_3 polluted air, and use of N_2O in anaesthesia.

The different N_2O forming processes are described in 3.2, and global emissions are assessed in 3.3 and 3.4. The sources of nitrous oxide are poorly known. Most of the observed fluxes show large spatial and temporal variation, so that even a great number of measurements is no guarantee for reliable emission estimates. On the other hand, N_2O is extremely stable in the atmosphere, and concentrations show little variation. A global mass balance of atmospheric N_2O can therefore be helpful in determining the total source strength, as illustrated in 3.3. Alternatively, results of several emission inventories are presented in 3.4. And finally, in 3.5 total emissions based on atmospheric N_2O are compared with the estimates according to inventories.

Table 3-1. Sources of N_2O considered in the present study

		Biogenic	*Abiogenic*
Natural		- biogenic processes in soils - biogenic processes in oceans - biogenic processes in other aquatic systems	- formation in the atmosphere - natural fires
Anthropogenic	Energy	- atmospheric NOx deposition on soils/waters	- stationary combustion of fossil fuels - stationary combustion of fuelwood - mobile combustion - atmospheric formation around high-voltage transmission lines
	Industry		- adipic acid production (nylon) - nitric acid production (fertilizer) - yet unidentified industrial processes
	Agriculture/land use change	- N input to soils: synthetic N fertilizers, animal manure, biological N fixation atmospheric NHx deposition; N input to waters by leaching and run-off - loss of soil N by decomposition and mineralization after savanna burning or forest conversion to agricultural land	- agricultural waste burning - biomass burning (savanna burning, shifting cultivation, deforestation)
	Waste	- N transformation in sewage treatment	- municipal solid waste incineration
	Other	- increased microbial activity by global warming - non-agricultural N input to surface waters[1] - atmosph.deposition of non-agricultural NH_3 - atmosph.deposition of non-agricultural NOx	- atmospheric formation in NOx/NH_3 polluted air[2] - anaesthesia

[1] N input from industry, households, sewage treatment plants, and atmospheric deposition; [2] NOx mainly from energy use and industries; NH_3 mainly from agriculture and industries

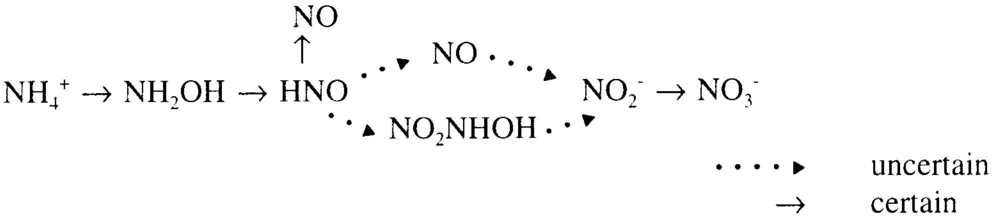
3.2 Processes responsible for N_2O production and consumption

3.2.1 Biogenic processes

Most of the N_2O in the earth's atmosphere is of microbiological origin. Many groups of microorganisms are capable of producing N_2O. In actual fact, most biological processes involving the oxidation or reduction of N through the +1 or +2 state can produce trace amounts of N_2O (Williams et al., 1992). However, the most important sources of N_2O are denitrification and nitrification, while only during denitrification can N_2O be consumed. Chemical decomposition of N oxides leading to N_2O formation is often referred to as chemodenitrification. Since chemodenitrification is microbially mediated it is treated as a biogenic process.

3.2.1.1 Nitrification

Nitrification is the biological oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) (Firestone and Davidson, 1989):



$$\begin{tikzcd}
 & & NO & & & \\
 & & & NO \arrow[dr, dotted] & & \\
NH_4^+ \arrow[r] & NH_2OH \arrow[r] & HNO \arrow[u] \arrow[ur, dotted] \arrow[dr, dotted] & & NO_2^- \arrow[r] & NO_3^- \\
 & & & NO_2NHOH \arrow[ur, dotted] & &
\end{tikzcd}$$

The most important of the genera of bacteria oxidizing NH_4^+ through to NO_2^-, is *Nitrosomonas*, while the oxidation of NO_2^- to NO_3^- is performed by *Nitrobacter*. Oxygen (O_2) is obligatory for nitrification, and nitrification rates generally decline as the oxygen availability declines.

Nitrous oxide has been shown to be a product of a reductive process in which ammonium-oxidizing bacteria use NO_2^- as an electron acceptor when oxygen is limiting (Poth and Focht, 1985). This mechanism is consistent with the observed increase in the production ratio $N_2O : NO_3^-$ with decreasing oxygen partial pressure. The elimination of nitrite may be a mechanism to prevent accumulation of NO_2^-, which is toxic to nitrifiers (Poth and Focht, 1985).

Nitrification is a constant process across many ecosystems. The supply of NH_4^+ forms its most important control (Firestone and Davidson, 1989). In natural ecosystems mineralization of organic matter is the major source of NH_4^+, while in agricultural systems NH_4^+ is mainly supplied by synthetic NH_4^+-yielding or organic fertilizers.

3.2.1.2 Denitrification

Denitrification can be defined as a group of processes during which NO_3^- or NO_2^- are reduced to the gaseous species NO, N_2O, or N_2. This definition includes both microbiological processes and abiotic reactions.

- *Biological denitrification.* Biological denitrification is the only process capable of producing and consuming N_2O. The following sequence for N-oxide reduction was proposed by Firestone and Davidson (1989):

$$\begin{tikzcd} & & NO \arrow[d, shift left] & & \\ NO_3^- \arrow[r] & NO_2^- \arrow[r] & {[X]} \arrow[r] \arrow[u, shift left] & N_2O \arrow[r] & N_2 \end{tikzcd}$$

General requirements for denitrification include (i) the presence of bacteria possessing metabolic capacity; (ii) the availability of reductants, mainly organic carbon; (iii) reduced O_2 availability; (iv) the availability of N oxides, NO_3^-, NO_2^-, NO, or N_2O (Firestone and Davidson, 1989).

The O_2 availability is the dominant factor limiting denitrification in habitats exposed to the atmosphere, such as soils. Contrary to this, in dominantly anaerobic habitats, such as sediments or poorly drained or inundated soils, the NO_3- availability is the major regulator. Where NO_3^- production via nitrification is inhibited in anaerobic soils, denitrification rates will also be low and denitrifiers may even consume N_2O as electron acceptor, turning these systems into a sink for N_2O. In non-fertilized soils with anaerobic zones, the NO_3^- availability may control denitrification rates, while in N-fertilized soils, the availability of carbon would limit denitrification.

Organisms capable of reducing NO_3^- to N_2 sometimes produce large amounts of N_2O at low O_2 levels, and sometimes none. This may be caused by several factors, one of them being the relative availability of reductant (mostly organic carbon) vs. oxidant (N oxides). If the availability of oxidants exceeds that of reductants, the oxidants may be incompletely utilized, i.e. N_2O will be not be reduced to N_2. Hence, N-oxide input in the form of inorganic N, such as synthetic N fertilizer, may lead to increased denitrification and also to increasing ratios $N_2O:N_2$ (Firestone and Davidson, 1989).

The O_2 availability in soils is influenced by the soil's drainage condition. It is also regulated by variable conditions affecting the O_2 availability, such as soil moisture and oxygen consumption by microorganisms and plants. High denitrification rates are sometimes observed in anaerobic micro-sites or hot spots, such as organic rich soil aggregates, in overall well-drained aerobic soils. This explains the high spatial variability of denitrification and N_2O losses (Parkin, 1987; Rappoldt, 1992). Wetting has been shown to stimulate N_2O production (Letey et al., 1981) causing high temporal variability. Thus rainfall may influence N_2O emissions considerably.

- *Chemodenitrification.* The formation of N_2O may result from decomposition of NH_2OH or from NO_2^-, both being intermediate products in nitrification (Davidson, 1991). The amount of N_2O produced in chemodenitrification is probably one order of magnitude smaller than the amount produced by biological denitrification (Williams et al., 1992).

3.2.2 Abiogenic processes

Several abiogenic sources of N_2O such as N_2O production in the troposphere, industrial emissions, and formation during combustion and burning can be distinguished (Table 3-1). Most, but not all, abiogenic sources are anthropogenic.

Formation of N_2O in the troposphere
In chapter 2.4 three mechanisms of N_2O production in the atmosphere were described. Nitrous oxide may be formed (i) by oxidation of NH_3 (ii) in a heterogeneous reaction between NH_3 and N_2O_5, and (iii) from excited N_2^* and O_2^*. These processes take place in unpolluted air. In air polluted with NH_3 and NOx, formation of N_2O via the pathways (i) and (ii) may be enhanced. Formation of N_2O via pathway (iii) may occur around high-voltage transmission lines.

N_2O formation during adipic acid prodution
Adipic acid (hexanedioic acid: $HOOC(CH_2)_4COOH$) is primarily used for the industrial production of nylon 6,6 polyamide. It is also used as plasticizer, lubricant, and for food acidulant, resins, plastics, and foams (Reimer et al., 1992). Adipic acid is produced in two steps (Reimer et al., 1992) and N_2O is produced during the second step:

(1) cyclohexane + air -> cyclohexane (K) + cyclohexanol (A)
(2) KA mixture + nitric acid -> adipic acid + N_2O

N_2O formation during nitric acid production
Industrial nitric oxide production generates N_2O. In the first step of nitric oxide production, the oxidation of ammonia to NO, N_2O is formed in a side reaction:

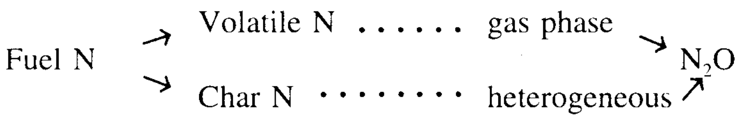
main reaction: $4\ NH_3 + 5\ O_2 \rightarrow 4\ NO + 6\ H_2O$
side reaction: $4\ NH_3 + 4\ O_2 \rightarrow 2\ N_2O + 6\ H_2O$

In the subsequent oxidation of NO to NO_2 and absorption to HNO_3, N_2O acts as an inert gas, so emissions are no longer affected.

Other industries
Adipic acid and nitric acid are the only known sources of N_2O produced industrially. It is, however, likely that there are more industrial sources of N_2O, that have not been identified yet (Olivier, 1993b; Oonk, pers.comm.). In fact, all processes where nitrogenous compounds are processed at relatively low temperatures (< 950 °C) are potential sources of N_2O. For instance, production of caprolactam, explosives, nitroglycerine, dodecanedioic acids and other dioic acids, all chemical productions in which nitrogen oxidation steps or (catalytic) reduction steps are involved, coking of coal, chlorination of water (e.g. in power plants), cement manufacture (pre-calciner), metal treatment processes and glass furnaces.

N_2O production during combustion processes

During combustion, N_2O can be formed from NOx and from fuel N. NOx stem from both fuel N and from atmospheric N_2 (De Soete, 1993). However, atmospheric N_2 is probably not an important source of N_2O in combustion, because at temperatures where NOx is formed from atmospheric N_2 (> 1300 °C) N_2O destruction rates exceed production rates. Only when temperatures drop (locally), slowing down N_2O destruction NOx from atmospheric N_2 can be a significant source of N_2O. Thus it can be assumed that most, but not all of the N_2O emitted originates from fuel N (Oonk, pers.comm.).



In the gas phase, N_2O may be formed when NO reacts with NCO or NH (reactions 1 and 2). At temperatures below 800 °C, N_2O production is slow, and at temperatures exceeding 950 °C, N_2O is rapidly broken down (reaction 3). Therefore, a maximum of N_2O emission occurs in the range 800 - 950 °C.

Heterogeneous processes include both N_2O formation and destruction. Non-catalytic heterogeneous reactions are the formation of N_2O from char-bound nitrogen atoms (reactions 4 and 5), the destruction of N_2O in bound carbon atoms (reactions 7 and 8), and N_2O formation from nitric acid and reduced sulfates (not shown). In addition, N_2O may be formed during catalytic NOx reduction (not shown).

Gas-phase processes

$NCO + NO \rightarrow N_2O + CO$ (800 - 950 °C) (1)

$NH + NO \rightarrow N_2O + H$ (800 - 950 °C) (2)

$N_2O + H \rightarrow N_2 + OH$ (>950 °C) (3)

Heterogeneous processes (predominant at temperatures of 700 - 800 °C)

$O_2 + (-C) + (-CNO) \rightarrow (-CO) + (-CNO)$ (4)

$(-CN) + (-CN) \rightarrow N_2O + 2(-C)$ (5)

$(-CNO) \rightarrow NO + (-C)$ (6)

$N_2O + (-C) \rightarrow N_2 + (-CO)$ (7)

$N_2O + (-CO) \rightarrow N_2 + CO_2$ (8)

NOx reduction and N_2O formation

On Pt/Rh three-way catalytic converters in cars, N_2O is formed by catalytic heterogeneous reactions. Catalytic heterogeneous production or destruction may also occur in other NOx reduction techniques, e.g. during catalytic NO reduction by hydrocarbons, and in fluidized bed combustion. Selective Catalytic Reduction (SCR) of NO may increase N_2O emissions, but this has only been observed in laboratories. In practice, full-scale SCR yields insignificant amounts of N_2O (Oonk, pers.comm.). Selective Non-Catalytic Reduction (SNCR) increases N_2O formation in practice. The most effective temperature for SNCR gives rise to high emissions of N_2O. More N_2O is formed when urea or cyanuric acid is used than when NH_3 is used in SNCR.

Stationary combustion of fossil fuels

The relative importance of homogeneous and heterogenous reactions differs per combustion process (De Soete, 1993). Most gaseous and liquid fuels have a low N content, so that only gas-phase N_2O chemistry is important. Emissions of N_2O can be expected to be low in most conventional power plants, where prevailing temperatures are high enough (> 1000 °C) to destroy most of the N_2O formed. Nevertheless, N_2O emissions from conventional power plants have been observed. These are thought to be the result of local temperature drops, which allow N_2O to be emitted before it is destroyed. In fluidized bed combustors (FBCs) all heterogeneous reactions described may occur, and may become predominant, caused by the high density of solid materials, the relatively low temperature (about 800 °C) at which FBC is operated, and the location of the heterogeneous reactions.

Mobile combustion

In vehicles without catalytic converters some N_2O is formed by gasphase reactions during the combustion process. Catalytic converters, however, increase N_2O formation in exhaust gases considerably. Catalytic converters in cars have been introduced to reduce emissions of NO, NO_2, CO, and hydrocarbons. There are several types of catalysts, including oxidation, and three-way catalysts. When operating under overall reducing conditions heterogeneous formation of N_2O occurs. This is particularly obvious in older three-way catalysts, in which N_2O is formed during NOx reduction on Pt/Rh (De Soete, 1993).

Biomass burning

Biomass N includes NH_3 or HCN type of compounds. During burning N_2O is formed maily from the HCN type. Fossil fuel N is virtually all HCN type, while in living biomass the NH_3 type prevails. Therefore, under the same conditions biomass can be expected as a smaller source of N_2O than fossil fuels. However, emissions of N_2O depend on the combustion efficiency, and burning of biomass is mostly an uncontrolled process. Local temperature drops, which promotes N_2O emission by reducing N_2O destruction rates, cannot be avoided especially during smouldering.

3.2.3 Indirect effects of environmental policy on N_2O emissions

Although there are hardly any N_2O measures taken at present, N_2O emissions can be affected by other environmental policies in several ways.

1. Reduction of NOx and NH_3 emissions will decrease the enhanced biogenic N_2O emissions induced by atmospheric deposition.
2. Catalytic NOx reduction can increase N_2O emissions during combustion; this is particularly obvious in 3-way catalytic converters in vehicles and SNCR in stationary combustion.
3. Several measures to reduce NH_3 emissions may increase N_2O emissions: (i) injection of fertilizers (including manure) instead of surface application (ii) deep litter stables, and (iii) nitric acid addition to manure (see chapter 4).
4. Volume-type measures to reduce energy use, fertilizer use, etc. may decrease the associated N_2O emissions simultaneously.

3.3 Global sources and sinks: an atmospheric mass balance

3.3.1 Pre-industrial global emission derived from atmospheric N_2O

In pre-industrial times human influences on the earth's atmosphere are assumed to have been negligible on a global scale. Atmospheric N_2O started to increase only in this century (Khalil and Rasmussen, 1992). Indeed, anthropogenic sources of N_2O are largely associated with human behavior typical for the 20th century: fossil fuel combustion, use of synthetic fertilizers, and industrial processes. The period prior to 1900 is therefore considered pre-industrial.

Nitrous oxide is one of the natural components of the earth's atmosphere. For an atmosphere in equilibrium global emissions of N_2O can be estimated as

Em = C/lft, where

Em = annual global emission of N_2O (Tg N y^{-1}),
C = globally averaged N_2O content of atmosphere (Tg N), and
lft = atmospheric lifetime (years).

The pre-industrial N_2O concentration may have been 285 (280 - 290) ppbv for many centuries (see chapter 2). The atmospheric lifetime of N_2O may be 120 (100 - 170) years (Prinn et al., 1990; Minschwaner et al., 1993). Assuming that 0.207 ppbv N_2O in the atmosphere represents 1 Tg N (Graedel and Crutzen, 1993), these ranges indicate that the pre-industrial emissions of N_2O were 11.5 (8.0 - 14.0) Tg N y^{-1} (Table 3-2). As a first approximation it seems reasonable to assume that pre-industrial emissions equal the present-day natural emissions.

Table 3-2. Pre-industrial global N_2O emissions (Tg N y^{-1}) estimated from pre-industrial concentrations and atmospheric lifetimes

Atmospheric lifetime	Pre-industrial concentration 280 ppbv	Pre-industrial concentration 285 ppbv	Pre-industrial concentration 290 ppbv
100 years	13.5	13.8	14.0
120 years	11.3	11.5	11.7
170 years	8.0	8.1	8.2

3.3.2 Emissions since 1900 derived from atmospheric N_2O

Atmospheric N_2O concentrations show little spatial variation in the troposphere, so that changes are easily determined. Atmospheric concentrations have been monitored systematically since the mid-seventies (chapter 2). According to Khalil and Rasmussen (1992) nitrous oxide started to increase rapidly only during the last century. Fig. 3-1 shows a scenario for global emissions which, when used as input in an atmospheric model, results in a reasonable simulation of the observed trend in atmospheric N_2O.

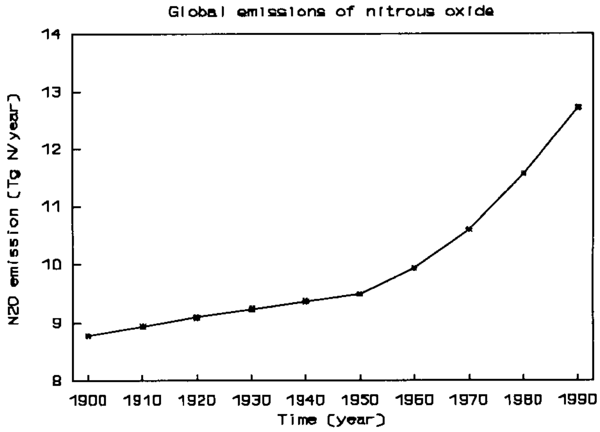


Fig. 3-1. Global emissions of nitrous oxide since 1900, which, when used as input in an atmospheric model simulates atmospheric concentrations of N_2O (Kroeze, 1994a).

The global pre-industrial emission of 11.5 (8.0 - 14.0) Tg N y^{-1} may be considered as the natural present-day emission. Khalil and Rasmussen (1992) used inverse modeling to deduce from atmospheric trends that anthropogenic N_2O emissions are 4.5 (3.9 - 5.1) Tg N y^{-1} at present. The global present-day emission may therefore amount to 16.0 (11.9 - 19.1) Tg N (Table 3-7).

3.4 Global sources and sinks: emission inventories

3.4.1 Inventories of emissions for 1990

This chapter overviews inventories of N_2O emissions from the literature (Table 3-3). Recent inventories show that total 1990 emissions may be 16.9 (9.6 - 27.6) Tg N y^{-1} (Table 3-3). About two-thirds of these emissions are natural (3.4.1.1). Anthropogenic sources include energy (3.4.1.2), industries (3.4.1.3), agriculture and land use change (3.4.1.4), waste (3.4.1.5), and other sources (3.4.1.6).

Figures 3-2 and 3-3 show that about one-third of current emissions are anthropogenic. Although the observed temperature of the earth may be a natural variation, the assciated N_2O emissions included in anthropogenic emissions in this chapter. Agriculture is one of the main individual N_2O sources. It should be realized that industrial emissions include N_2O emitted during the production of fertilizers. Food production is responsible for about 50% of the present anthropogenic emissions.

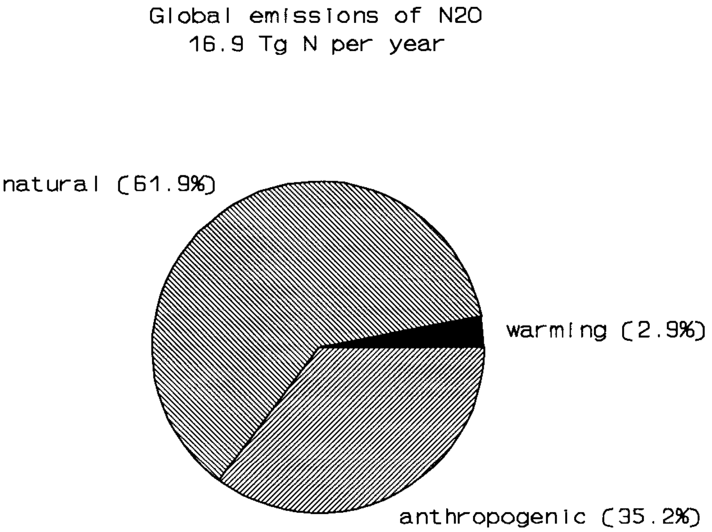


Fig. 3-2. Global 1990 emissions of nitrous oxide (see Table 3-3).

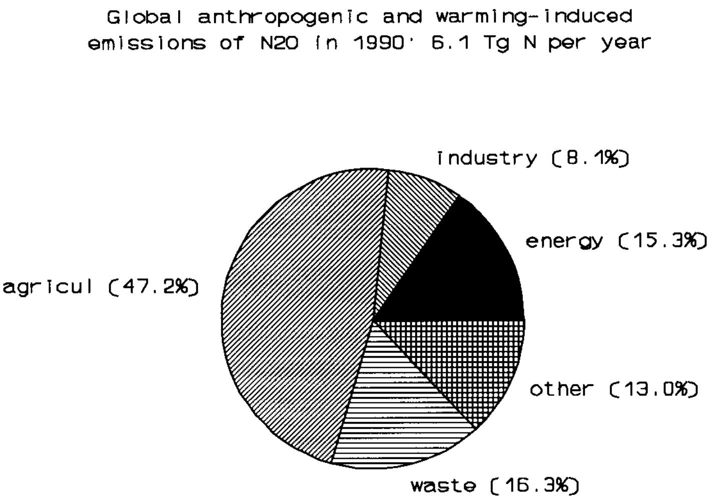


Fig. 3-3. Global 1990 anthropogenic emissions of nitrous oxide (see Table 3-3).

Table 3-3. Present worldwide N_2O emissions (Tg N y^{-1}) according to recent inventories and derived from atmospheric N_2O; n.q. = not quantified

Source	N_2O emission (Tg N y^{-1})	References
Recent inventories of natural sources (chapter 3.3.1)		
Soils	6.6 (6.6 - 6.8)	2
Oceans	3.8 (1.4 - 5.7)	3
Freshwater and coastal waters	0.1 (0.0 - 0.4)	4
Atmospheric formation	0.3 (0.1 - 0.8)	5
Total natural	10.8 (8.1 - 13.7)	
Recent inventories of anthropogenic sources (chapter 3.4.1)		
Energy		
- fossil fuels: stationary combustion	0.1 (0.0 - 0.3)	6,7
- fossil fuels: mobile combustion	0.4 (0.2 - 0.6)	6,7
- fuelwood	0.1 (0.1 - 0.2)	2,14
- NOx deposition	0.3 (0.0 - 0.7)	9
- high-voltage transmission lines	n.q.	
Industrial processes		
- nitric acid production	0.2 (0.1 - 0.3)	10,2
- adipic acid production	0.3 (0.2 - 0.4)	7,10,11,2
- unidentified industrial processes	n.q.	
Agriculture and land use change		
- synthetic nitrogen fertilizer	1.0 (0.1 - 1.6)	12,2,13
- animal manure[1]	1.0 (0.1 - 2.0)	12,2,13
- leaching, runoff	0.3 (0.0 - 3.6)	9,4
- biomass burning (savanna/shifting cultivation/deforestation)	0.1 (0.0 - 0.2)	2,8,14
- post-burning soil emissions	<0.1 (0.0 - 0.2)	2,14
- agricultural waste burning	0.1 (0.1 - 0.2)	2,14
- tropical forest conversion	0.4 (0.2 - 0.7)	2,14
Waste		
- sewage treatment (non-agricultural)	1.0 (0.2 - 1.9)	6
- municipal solid waste incineration	n.q.	
Other		
- atmospheric formation	0.3 (0.2 - 0.4)	5
- anaesthesia	n.q.	
- global warming	0.5 (0.0 - 0.6)	15,16
Total anthropogenic[17]	6.1 (1.5 - 13.9)	
Recent inventories: total		
Anthropogenic + natural	16.9 (9.6 - 27.6)	

1. Including N_2O emissions induced by atmospheric NHx deposition; 2. Bouwman et al., in prep.; 3. Nevison, 1994; Butler er al., 1989; 4. This report, based on Seitzinger, 1988; 1990 and Meybeck, 1982; 5. Dentener, 1993; 6. Khalil and Rasmussen, 1992; 7. Watson, 1992; 8. Crutzen and Andreae, 1990; 9. This report; 10. Olivier, 1993a; 11. Reimer et al., 1992; 12. Bolle et al., 1986; 13. Kroeze, 1994a; 14. Estimated uncertainty range -50% to +100%; 15. Khalil and Rasmussen, 1989; 16. Kreileman and Bouwman, 1994; 17 Incl. warming-induced emissions, which may be natural

3.4.1.1 Natural sources

Recent emission inventories indicate that natural N_2O emissions are 10.8 (8.1 - 13.7) Tg N y^{-1} (Table 3-3). Almost two-thirds of these emissions are from soils (Fig. 3-4). It is assumed that emissions from biomass burning are virtually all anthropogenic.

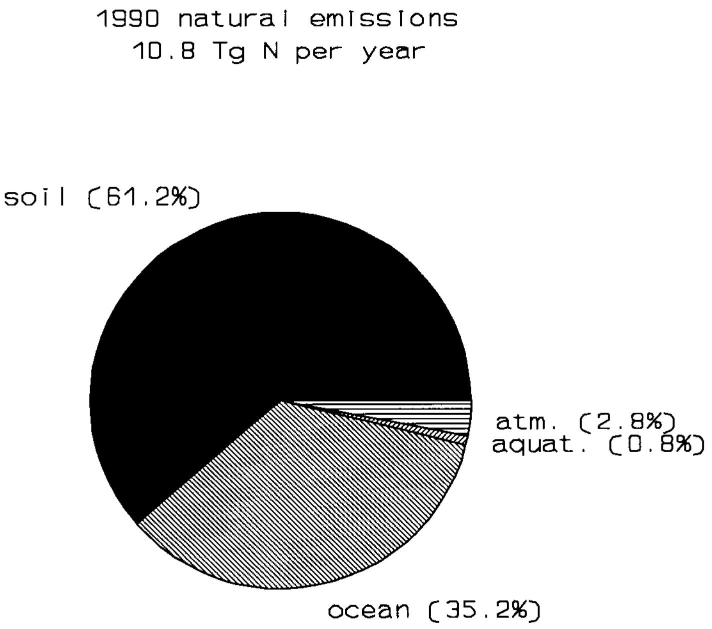


Fig. 3-4. Natural sources of N_2O, including soils, oceans, other aquatic sources (aquat.) and atmospheric formation (atm.)

Natural emissions from soils

Emissions of N_2O from soils in a world without human influences, but for the current land cover, are calculated by Kreileman and Bouwman (1994) to be 6.6 Tg N y^{-1}. They used a slightly different version of the model of Bouwman et al. (1993), who calculated this source of N_2O to be 6.8 Tg N y^{-1}. These models simulate the potential N_2O production in undisturbed soils in a 1° x 1° grid as a function of organic matter input, temperature, soil water status, soil fertility, and oxygen availability. In doing so, about 60% of the observed variability in N_2O emissions from soils could be explained. Tropical ecosystems were found to be major contributors to the natural global N_2O budget, probably because the year-round high temperatures and high nitrogen turnover rates result in high N_2O emissions. This was also concluded by Matson and Vitousek (1990), Prinn et al. (1990) and Roberston (1993).

Natural emissions from oceans

The world oceans form a significant source of N_2O. Supersaturation of oceanic surface waters was measured by Butler et al. (1989) and Weiss et al. (1992). Nevison (1994) presented an estimate range the ocean source of 2.8 - 5.7 Tg N y^{-1} based on these data. This estimate will be updated in Nevison et al., (in press). One of her calculations, yielding an emission of 3.8 Tg N y^{-1}, is most close to the average of the range. Nevison's estimate is considerably higher than the 2 (1.4 - 2.6) Tg N y^{-1} presented by IPCC, which was based on Butler's data only (Watson, 1992).

Emissions of N_2O are not evenly distributed over the world's oceans. Several regions of high N_2O emissions exist. These may be upwelling regions, where deep water, cold and rich in nutrients, mixes with surface water. High emission rates were, for instance, observed in the upwelling region of the Indian Ocean (Law and Owens, 1990; De Wilde, 1993). Nevison (1994) identified the Northern Pacific, the Equatorial Upwelling Zone and the water off the coast of Antarctica as particularly strong sources of regions. Ocean N_2O emissions may be enhanced by increasing N input from anthropogenic sources.

Natural emissions from freshwater and coastal waters systems

Biological activity is low in the open ocean if compared to coastal waters, estuaries, and freshwater systems. Therefore one could expect higher emissions of N_2O from these aquatic systems than from the open ocean (Seitzinger, 1990). Indeed, supersaturation of N_2O in coastal and freshwater systems is usually higher than in open oceans, with exception of oceanic upwelling regions such as the Indian Ocean.

Nitrifying and denitrifying bacteria are the most important N_2O producers in aquatic systems. Terrestrial systems form an important source of nitrogen in coastal waters. Nitrogen may leach or run-off to rivers, and be transported to seas. This is a natural process which has been enhanced by human activities, since much of the leached nitrogen is from fertilization, livestock manure, sewage water, or industries.

In pre-industrial times the non-ocean aquatic systems were probably not very important sources of N_2O, since leaching of nitrogen from undisturbed terrestrial systems is probably low. Meybeck (1982) estimated natural nitrogen transport rates in rivers at about 35 Tg N y^{-1}. About half (1 - 75%) of the N input to rivers may be denitrified (Seitzinger, 1990). The ratio of N_2O to N_2 fluxes from sediments in rivers, streams and benthic sediments is often within the range 0.1 - 0.4% (Seitzinger, 1988). Thus natural N_2O emissions may amount to 0.25 (0.1 - 0.4)% of N removed by denitrification, or 0.1 (0.0 - 0.4) Tg N y^{-1}.

Formation of N_2O in the atmosphere

As described in chapter 2.4, three mechanisms of N_2O formation in the troposphere have been proposed in the literature. Only one of these global production rates has been quantified. Dentener (1993) calculated that in an undisturbed atmosphere, 0.3 (0.1 - 0.8) Tg N may be formed annually from oxidation of NH_3 (Table 3-3). For the other mechanims mentioned in chapter 2 no estimates exist, so that 0.3 Tg may be an underestimation for formation of N_2O in the troposphere.

3.4.1.2 Energy (stationary and mobile combustion)

Combustion of fossil fuels has for years erroneously been considered the most important source of anthropogenic N_2O. This was the result of unknown formation of N_2O after sampling (Muzio and Kramlich, 1988). The reported high N_2O concentrations up to 200 ppmv in conventional power plant exhaust (e.g. Hao et al., 1987) are nowadays considered artefacts. Nevertheless, fossil fuel burning, and in particular mobile combustion, is still a considerable source of N_2O (Fig. 3-5). Total emissions are estimated at 0.9 (0.3 - 1.8) Tg N y^{-1}.

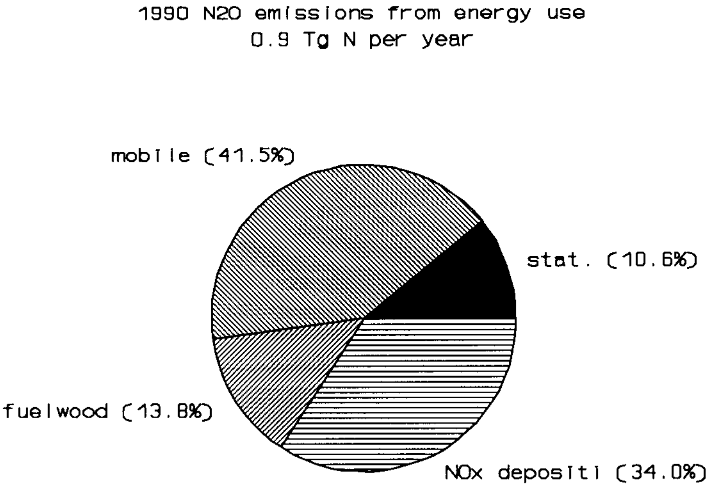


Fig. 3-5. Global 1990 N_2O emissions from mobile combustion, stationary combustion, fuelwood and atmospheric deposition of NOx (Table 3-3).

Direct N_2O emissions from stationary combustion

Recent N_2O measurements in exhaust gases power plants show that N_2O concentrations in the flue gases are usually less than 5 ppmv (e.g. Linak et al., 1989; 1990; Sloan and Laird, 1990; Yokoyama and Nishinomyia, 1991). However, N_2O concentrations can be higher. For instance, fluidized bed combustors are potentially larger sources of N_2O (Spoelstra, 1993). In some gasturbines elevated concentrations have been observed (Spoelstra, 1994). Some NOx reduction techniques are a potential source of N_2O which cannot be quantified because of lack of data (see 3.2.2).

The significance of N_2O production in conventional power plants is a matter of discussion. Most observed N_2O concentrations range from lower than the ambient concentration (< 0.3 ppmv) to 2 ppmv. Since these values are often at the lower end of the detection limit of the equipment used, it is difficult to obtain emission facors. Some authors therefore suggest that these emissions are negligible, while others report small emissions. Some studies even suggest N_2O consumption in some power plants. According to Khalil and Rasmussen (1992) and Watson (1992) direct N_2O emissions from stationary sources are estimated globally at 0.1 (0.0 - 0.3) Tg N y^{-1} (Table 3-3).

Direct N_2O emissions from mobile combustion

Vehicles, especially when equipped with three-way catalytic converters, are a potentially important source of anthropogenic N_2O. De Soete (1993) concluded that new catalytic converters may increase N_2O emissions from vehicles by a factor of 3.8 - 4.9. Aged catalytic converters may even increase N_2O emissions by a factor of 10 - 16.

Estimates on current global N_2O emissions range from 0.2 - 0.6 Tg N y^{-1} (Khalil and Rasmussen, 1992; Watson, 1992). Based on emission factors as reported by Baas (1991) global N_2O emissions are estimated at 0.4 Tg N y^{-1} (Kroeze, 1994a). Since three-way catalytic converters are being introduced on a large scale at present, this source of N_2O is increasing relatively fast worldwide.

N_2O emissions from fuelwood combustion

Emissions from fuelwood combustion are 0.1 Tg N y^{-1} according to Bouwman et al. (in prep.). The uncertainty range may be -50% to +100%. This is in agreement with Crutzen and Andreae (1990).

N_2O emissions induced by NOx deposition

Other nitrogen oxides (NO, NO_2) emitted during burning of fossil fuels, may, after deposition of soils and oceans, cause biogenic N_2O emissions to increase. For example, Brumme and Beese (1992) showed that after two decades of atmospheric deposition of acidifying compounds (ammonium and sulphuric acid), N_2O emissions from German forest soils were enhanced by up to a factor of 5. Reported rates of N_2O-N emissions are 0.2 and 1.6% of the amount of nitrogen deposited onto soils (Bowden et al., 1991; Brumme and Beese, 1992). Annual worldwide NOx emissions due to fossil fuel combustion may amount to 24 (14 - 28) Tg N y^{-1} (Houghton, 1992; Logan, 1983), and from biomass burning 8 (2.5 - 13) Tg N y^{-1} (Houghton, 1992). Assuming that 1% (0.2% - 1.6%) of the nitrogen deposited is emitted as N_2O, this source may amount to 0.3 (0.0 - 0.7) Tg N y^{-1} (Table 3-3).

N_2O emissions due to discharges of high-voltage transmission lines

Atmospheric N_2O formation in coronal discharges around high voltage transmission lines may occur (Fraser et al., 1990). This source cannot be quantified at present (Table 3-3).

N_2O formation in polluted air

Formation of N_2O may occur in air polluted with NOx, SOx, and NHx (Adema et al., 1990; Dentener, 1993). This anthropogenic source is included in the category "other", because the contributions of the energy and agricultural sector cannot be separated (Table 3-3).

3.4.1.3 Industry

Total industrial emissions are 0.5 (0.3 - 0.7) Tg N y^{-1}, of which 60% is from adipic acid production, and 40% from nitric acid production. There may, however, be still unidentified industrial sources of N_2O (Fig. 3-6).

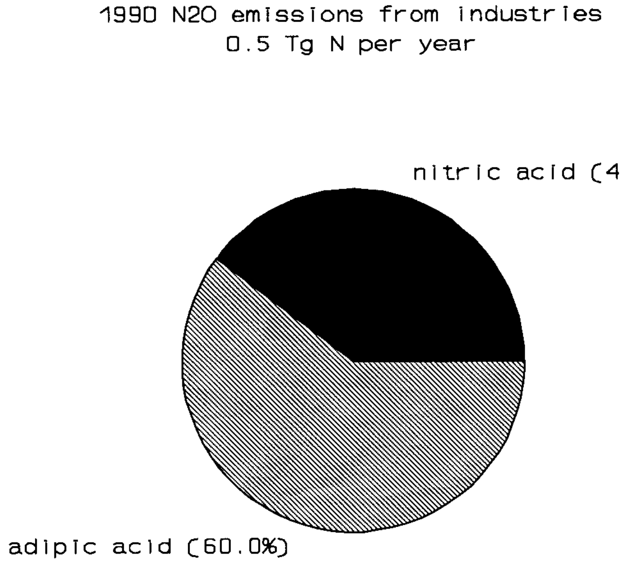


Fig. 3-6. 1990 global emissions from industrial sources (Table 3-3).

Emissions during nitric acid production
Nitric acid (HNO_3) is mainly produced as an intermediate in fertilizer production. Reported emission factors, based on measurements, range from 7 - 27 g N_2O-N per kilogram of HNO_3-N produced (Reimer et al., 1992; Olivier, 1993a). Global production of nitric acid amounts to 11 - 14 Tg N y^{-1} (Bouwman et al., in prep.). Therefore, N_2O emissions are estimated 0.2 (0.1 - 0.3) Tg N y^{-1} (Table 3-3).

Emissions during adipic acid production
At present 1.8 Tg adipic acid is produced, mainly as a feedstock for nylon 6,6 (Olivier, 1993a). Related N_2O emissions amount to 300 g N_2O per kilogram adipic acid (Thiemens and Trogler, 1991; Olivier, 1993a), or 0.4 Tg N_2O-N y^{-1}. Actual emissions are fewer, since adipic acid producers have already taken action to avoid N_2O emissions. Reimer et al. (1992) assumed a present global abatement of 32%. Nitrous oxide emissions are estimated at 0.3 (0.2 - 0.4) Tg N y^{-1} in Table 3-3 (Bouwman et al. in prep.).

More industrial sources
Olivier (1993b) reports potential industrial sources of N_2O that are not associated with production of nitric or adipic acid. Some examples are production of caprolactam, explosives, nitroglycerine, dodecanedioic acids and other dioic acids, all chemical productions in which nitrogen oxidation steps or (catalytic) reduction steps are involved, coking of coal, chlorination of water (e.g. in power plants), cement manufacture (pre-

calciner), metal treatment processes and glass furnaces. Olivier recommended further investigation of the exact origin of this source. Clearly, any process using an N compound, or a catalytic reduction step, may be a source of N_2O.

3.4.1.4 Agriculture and land use change

Agricultural emissions are estimated at 2.9 (0.5 - 8.5) Tg N y^{-1} (Table 3-3; Fig. 3-7). These emissions are largely associated with the use of fertilizer and animal manure, which also represent a major cause of nitrogen leaching and run-off (Fig. 3-7).

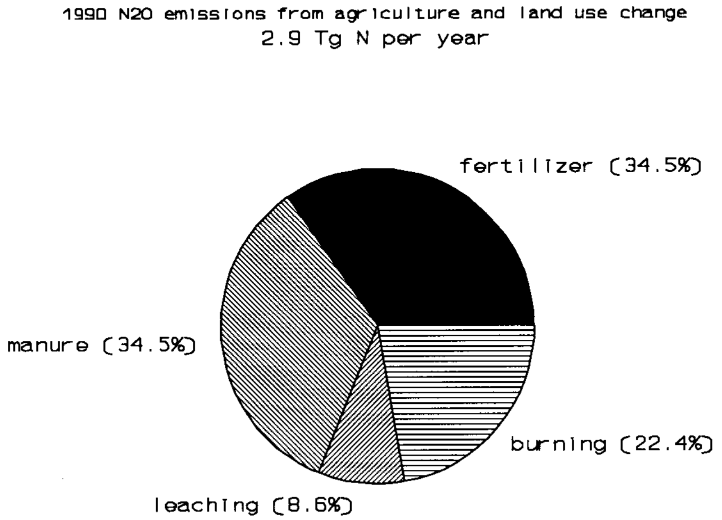


Fig. 3-7. 1990 agricultural emissions of N_2O from agriculture

Synthetic fertilizer-induced soil emissions

Biogenic N_2O production in soils is enhanced by synthetic nitrogen fertilizers and animal manure. Reported emission factors for N_2O-N range from 0.1 - 2% of the amount of fertilizer N applied (Bolle et al., 1986; Eichner, 1990), which implies 0.1 - 1.6 Tg N_2O- N y^{-1} for the global N-fertilizer use of 80 Tg y^{-1} (Table 3-3). In a global study, Bouwman et al. (in prep.) analyzed two different methods to estimate fertilizer-induced N_2O release:

(i) The first is the method proposed by Eichner (1990), which has frequently been cited. The emission factors are specified for the different N fertilizer types. The mean emission rate for the 1990 global fertilizer mix is 0.3 (0.1 - 1.1)% (Table 3-4). This represents the fertilizer-induced emissions, calulated as the difference in flux between fertilized plots and control plots. Eichner (1990) used studies during which N_2O fluxes had been observed for less than a year, and excluded studies where fertilizer application rates were over 250 kg N ha^{-1} from her calculations because of lack of representiveness for global application rates. Eichner proposed a doubling of this estimate to 0.5% in order to account for N_2O-N emissions after nitrogen leaching and run-off, and for N_2O emissions outside the sampling period, yielding a global emission of about 0.4 Tg N y^{-1}.

(ii) Bouwman et al. (in prep.) and Bouwman (1994) derived an emission factor from experiments where N_2O fluxes were measured during a full year in several locations. In these experiments the fertilizer-induced N_2O-N emissions equalled 1.25% of fertilizer N applied, which is about 1 Tg N y^{-1} for the global N fertilizer use. Fertilizer applications up to 500 kg N ha^{-1} were included in this analysis. In order to obtain total soil emissions from agricultural soils, the "background" emissions should be added to the fertilizer-induced emissions. Background emissions from arable lands may be 0.9 - 1.4 Tg N y^{-1} (Bouwman et al., in prep.) and these are included in the category "natural" here (chapter 3.4.1.1).

The estimate for annual N_2O emissions in Table 3-3 is based on the second method, resulting in 1.0 Tg N y^{-1}. This is considerably higher than Eichner's estimate. Using one emission factor for all types of fertilizers in all situations may seem inappropriate. However, present knowledge seems insufficient to derive reliable emission factors. Type of fertilizer may be one of the determinants in N_2O production (Table 3-5), but other factors may be as important (Mosier, 1993; Langeveld and Hofman, 1994). These include temperature, moisture content of the soil, partial pressure of oxygen, soil acidity, the availability of readily decomposable organic matter, and management practices (Table 3-5).

Animal manure

Animal manure contains nitrogen and is therefore a potential source of N_2O. The N_2O emissions from nitrogen excretion from animal husbandry are anthropogenic. Emissions from wild animals are natural, though unimportant on the global scale (Bouwman et al., in prep.). Release of N_2O may occur from manure in stables, during storage of manure or in the field. Measurements on N_2O fluxes from manure are scarce. Few studies report global estimates. There is much uncertainty about emission factors to be used. In addition, the amount of nitrogen produced by livestock, especially in tropical regions, is not easily quantified. The nitrogen excretion depends on many factors, such as animal weight, type of food and climate.

Globally, about 100 Tg of N y^{-1} is excreted in manure (Bouwman et al., in prep). For animal manure emission factors similar to those used for synthetic fertilizers are used, because the N_2O formation is basically the same process. Thus N_2O-N emissions from manure could be 1 (0.1 to 2)% of the manure nitrogen produced, or 1.0 (0.1 - 2.0) Tg N y^{-1} (Table 3-3). This estimate includes N_2O emissions resulting from atmospheric deposition of ammonium. This total is in agreement with results of Nevison (1994) and Kroeze (1994a). The contribution from animal waste from confined animals may be 0.2 - 0.6 Tg N y^{-1}, based on observed excess N_2O : excess CH_4 in air from stables and barns (Khalil and Rasmussen, 1992). The background emission from the world's grasslands may be 1.4 - 1.5 Tg N y^{-1}, and is included in the natural emissions (chapter 3.4.1.1).

Atmospheric formation in NH_3 polluted air

If N_2O is formed in polluted air containing NOx and NH_3, it is difficult to determine the contributions of the agriculture (NH_3 emissions) and the energy sector including traffic (NOx emissions) to this source. Therefore in Table 3-3 anthropogenically induced formation of N_2O in the troposphere is included in the category "other".

Nitrogen leaching and run-off

In addition to direct N_2O release to the atmosphere the nitrate and N_2O leached from agricultural soils may lead to N_2O emissions at remote locations from groundwaters and surface waters. Kilmer (1979) gives crude estimates on the fate of synthetic nitrogen fertilizers applied to agricultural soils around the world. Approximately 50% of the nitrogen applied is harvested in crops. After consumption most of this nitrogen is translocated to manure, compost, or sewage. Another 10 - 30% of the nitrogen applied as fertilizer may leach from soils. Approximately 10 - 20% is volatilized, while up to 30% of the nitrogen may accumulate in soils, or is lost by wind erosion, water erosion, or other mechanisms. Thus a major part of the fertilizer N is transported from the agricultural field where applied, and can be nitrified or denitrified elsewhere causing N_2O emissions elsewhere. Although about half of the fertilizer N used is taken up by crops, most of it is, over the years, returned to the atmosphere as NH_3, N_2O or N_2 (Duxbury et al., 1993).

Although few data are available, it has been suggested that the resulting remote N_2O emissions are equal in size to the fertilizer-induced soil emissions from agricultural fields (Eichner, 1990; Ronen et al., 1988).

Annual anthropogenic N input to soils is at present at least 200 Tg N y^{-1} (100 Tg N y^{-1} manure, 80 fertilizer, at least 20 atmospheric deposition (Houghton et al., 1992), and an unknown amount of biological N fixation). According to Seitzinger (1988; 1990), 0.2 - 0.4% of N nitrified or denitrified in rivers and estuaries is lost as N_2O. In highly polluted areas, however, this percentage may be as high as 6%. In addition, the nitrogen may be denitrified during transport from soils to the rivers. If 25 (10 - 30)% of the N input to soils leaches, and 0.5 (0.2 - 6)% of nitrogen entering rivers is lost as N_2O, aquatic emissions could amount to 0.3 (0.0 - 3.6) Tg N y^{-1}.

Biomass burning: savannas, shifting cultivation and deforestation

During biomass burning N_2O can be formed from N in biomass or from atmospheric nitrogen (Crutzen and Andreae, 1990). Abiogenic emissions amount to 0.1 Tg N y^{-1} (Bouwman et al. in prep.), with a range of unvertainty of -50% to +100%.

Post-burn effects of savanna burning

Biogenic soil emissions of N_2O may, at least temporarily, be enhanced after the fire. Post-burn effects as a result of savanna and grassland burning may be <0.1 Tg N y^{-1} (Bouwman et al. in prep.). The range of uncertainty in these estimates is tentatively set at -50% to +100%.

Burning of agricultural waste

Bouwman et al. (in prep.) estimated that emissions of N_2O from agricultural waste burning are 0.1 Tg N y^{-1}, based on carbon released and C/N ratios of the biomass burned and emission factors from Crutzen and Andreae (1990). Again, the range of uncertainty is set at -50% to +100%.

Tropical forest conversion (post-burn effects of deforestation)

Clearing of vegetation, which is mostly done by burning, causes acceleration of decomposition and mineralization of soil organic matter. The nitrogen mineralized can be easily nitrified or denitrified. When the soils are not fertilized after the clearing, N_2O emissions decrease with time. Ten years after clearing, N_2O emissions from tropical pastures may even be lower than before clearing (Keller et al., 1993). In temperate zones major land use changes took place in the previous centuries. At present, changes in land use are most pronounced in the tropics. Bouwman et al. (in prep.) estimated N_2O emissions from tropical forest conversion to be 0.4 Tg N y^{-1} (Table 3-3), assuming that soil emissions are enhanced for 10 years after forest clearing, and that thereafter emissions are lower than pre-clearing emissions. The range of uncertainty may be -50% to +100%.

Atmospheric NHx deposition

Animal manure is a source of atmospheric NH_3. Deposition of ammonium onto soils may, like NOx deposition, enrich soils with nitrogen, and thus increase N_2O emissions. This source is included here in the manure-related emissions.

Table 3-4. N_2O-N emission factors as reported by Eichner (1990) and Bouwman (1994) in fertilizer N appplied (%)

	Median	Range
Eichner		
Anhydrous ammonia[1]	1.63	0.86 - 6.84
Annmonium nitrate[1]	0.40	0.04 - 1.71
Ammonium type[1]	0.12	0.02 - 0.90
Urea[1]	0.11	0.07 - 0.18
Nitrate[1]	0.03	0.001 - 0.50
Total for fertilizer mix used in 1990[2]	0.26	0.10 - 1.09
2 x total for fertilizer mix in 1990[3]	0.52	0.20 - 2.18
Bouwman		
Fertilizer induced N_2O loss[4]	1.25[5]	0.2 - 2.5%

[1] Emissions during sampling period only; [2] Emissions during sampling period only; Bouwman et al. (pers.comm.); [3] Including emissions outside sampling period and off-site emissions; [4] Excluding background emissions; leaching losses not included; range differs slightly from Bouwman (1994); [5] average

Table 3-5. Key factors affecting fertilizer-derived N_2O emissions (Eichner, 1990)

Management practices	Environmental factors
Fertilizer type	Temperature
Application rate	Precipitation
Application technique	Soil moisture content
Timing of application	Organic C content
Tillage practices	Oxygen availability
Use of other chemicals	porosity
Crop type	pH
Irrigation	Freeze and thaw cycle
Residual N and C from crops and fertilizer	Microorganisms

3.4.1.5 Waste

Sewage treatment

Sewage treatment plants are a known source of N_2O, formed by nitrifying and denitrifying bacteria from sewage nitrogen. The estimate of Khalil and Rasmussen (1992) for this source of N_2O is 1.0 (0.2 - 1.9) Tg N y^{-1} (Table 3-3).

Municipal Solid Waste (MSW) incineration

Incineration of municipal solid waste (MSW) is another source of N_2O. Measurements in the Netherlands indicated that per ton of domestic waste 12.7 g N_2O-N is emitted (Spoelstra, 1993). A global source strengh is, however, not known.

3.4.1.6 Other sources

The category "other" includes formation of N_2O in the polluted troposphere and enhanced biogenic emissions as a result of global warming (Fig. 3-8). The latter may not be anthropogenic.

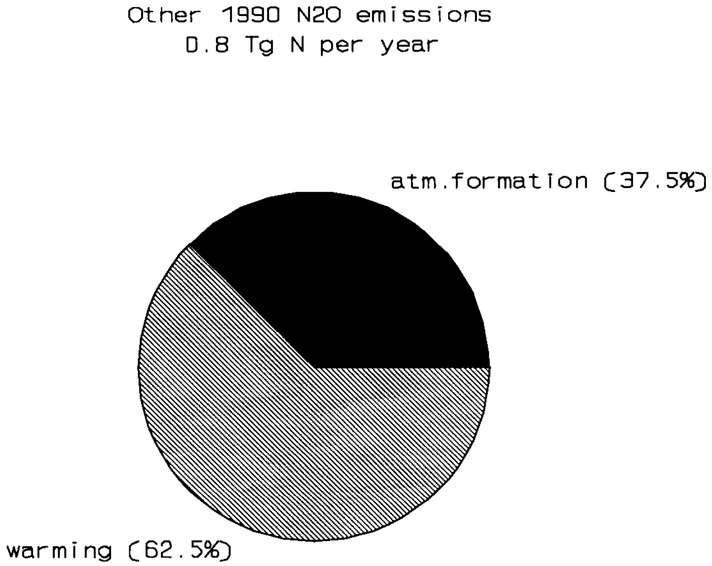


Fig. 3-8. 1990 global N_2O emissions: atmospheric formation emissions induced by global warming (Table 3-3).

Atmospheric formation

Formation of N_2O may occur in air containing NH_3 and NO_2 (see 2.4). According to Dentener (1993) the anthropogenic part of this source may amount to 0.3 (0.2 - 0.4) Tg N_2O-N y^{-1} (Table 3-3, Fig. 3-8). Anthropogenic emissions of NH_3 are mainly agricultural. Emissions of NOx are mainly the result of fossil fuel use and industry.

Global warming

Microbial activity depends on the temperature of the environment. Therefore it is likely that biogenic emissions of N_2O will increase along with the surface temperature of the earth. Indeed, during ice ages, the atmospheric N_2O concentrations dropped, indicating that global emissions are affected by the global temperature. Khalil and Rasmussen (1989) concluded that during the little Ice Age global emissions reduced about 0.3 Tg N_2O-N per degree temperature decrease. Kreileman and Bouwman (1994) concluded using a soil model that N_2O emissions could increase by 1.1 Tg N y^{-1} per degree warming. The temperature of the earth has increased by 0.45 $\pm$ 0.15 °C since the beginning of the century (Folland et al., 1992). Thus global N_2O emissions could have increased by 0.5 (0 - 0.6) Tg N y^{-1} (Table 3-3, Fig. 3-8). The present warming can be a natural variation. Nevertheless it is included in the anthropogenic source here.

Other sources

The emissions described so far may not cover all anthropogenic N_2O emissions. For instance, non-agricultural nitrogen loading of surface waters, and deposition of non-energy related NOx and non-agricultural NHx are not included.

3.4.2 Emission since 1900 according to emission inventories

Table 3-6 shows estimated trends in N_2O emissions since 1900. Clearly, anthropogenic N_2O emissions have increased considerably since 1950. The decadal growth in emissions in the second half of this century was much higher than in the first half.

In the beginning of this century, anthropogenic N_2O emissions arose mainly from biomass burning and animal manure. Between 1900 and 1950 anthropogenic emissions more than doubled, mainly as a result of increasing livestock numbers and increasing biomass burning. Both trends were the result of a growing world human population.

Between 1950 and 1990 anthropogenic N_2O emissions increased by at least a factor of 3. This is mainly a result of increased agricultural activities (synthetic nitrogen fertilizer production, animal population, biomass burning), but also a result of industrial production of nitric acid and adipic acid, and fossil fuel combustion. The global emissions from vehicles (mobile sources) has been of growing importance during the last decades as is mainly associated with the introduction of the 3-way catalytic converters in cars in developed countries, meant to reduce NOx emissions. Between 1980 and 1990 N_2O emissions from transport probably increased by a factor of 4. By 2000 these emissions could be more than 12 times as high as emissions in 1980 (Kroeze, 1994a).

Emissions of N_2O as a result of global warming are included in the table. However, it is not clear whether the temperature trends observed should be attributed to an enhanced greenhouse effect. If the global warming observed appears to be due to a natural fluctuation, the resulting changes in N_2O emissions must be considered natural fluctuations as well.

Table 3-6. Estimated worldwide anthropogenic emissions of N_2O (Tg N y^{-1}) in 1900, 1950, and 1990[1]

Source	1900	1950	1990
Energy	<0.1	<0.1	0.9
Industry	0.0	<0.1	0.5
Agriculture and land use change	0.4	0.7	2.9
Waste	0.3[3]	0.5[3]	1.0
Other[2]	<0.1	0.4	0.8
Total	0.7	1.6	6.1

[1] 1990 data from Table 3-3; other data estimated based on Kroeze (1994a); [2] Including global warming-induced emissions, which may be a natural variation; [3] Increase based on population growth.

3.4.3 Sinks of N_2O

Atmospheric N_2O is broken down mainly in the stratosphere, as described in chapter 2. Stratospheric destruction amounts to about 9 - 13 Tg N y^{-1} at present. In addition, soils and surface waters may be a sink for atmospheric N_2O. In most studies, however, these are considered negligible. Soils may be a sink for N_2O, since denitrifying bacteria can reduce N_2O to N_2. For instance, Ryden (1981) found an agricultural soil to be alternatively a source and sink of N_2O. The soil acted as a sink at moderate to high soil water content (> 20% by weight), while the mineral N content was low (while total N was high), and temperatures were between 5 and 8 °C. When mineral N content was higher, the soil acted as a source. This could mean that natural soils, where mineral nitrogen concentration is usually low, have the potential to absorb N_2O. Ryden suggests that the N_2O consumed is reduced during denitrification. Nitrous oxide consumption has also been observed in wetlands (Hutchinson and Davidson, 1993).

3.5 Conclusions

This chapter describes and quantifies global sources and sinks of nitrous oxide. Biogenic formation of N_2O occurs in soils and waters during nitrification and denitrification. These are biological processes, during which N_2O is formed as a by-product or intermediate. Biogenic N_2O formation is enhanced by human activities, in particular by nitrogen input to soils (fertilizers, manure, biological N_2 fixation and atmospheric deposition). Abiogenic formation of N_2O occurs during combustion processes and in the atmosphere. Most abiogenic formation is the result of human activities such as fossil fuel and biomass burning.

Global emissions were derived in two ways in this chapter. First, trends in atmospheric concentrations are used to derive global N_2O emissions (3.3). Second, emissions according to recent inventories are reviewed in 3.4. The results of both methods are compared in Table 3-7.

Inventories of N_2O emissions indicate that the global emissions for 1990 may be 16.9 (9.6 - 27.6) Tg N (3.5). This is in good agreement with the total based on atmospheric concentrations of 16.0 (11.9 - 19.1) Tg N y^{-1}. For natural emissions the two totals are in reasonable agreement: 10.8 (8.1 - 13.7) Tg N y^{-1} for inventories and 11.5 (8.0 - 14.0) Tg N y^{-1} for the estimate based on atmospheric N_2O. The total for anthropogenic N_2O emissions from inventories, 6.1 (1.5 - 13.9), is higher than the 4.5 (3.9 - 5.1) Tg N y^{-1} derived from trends in atmospheric N_2O. Some anthropogenic sources may therefore have been overestimated in recent inventories as presented in Table 3-3.

Anthropogenic sources of N_2O are from energy (0.9 Tg N y^{-1}), industry (0.5 Tg N y^{-1}), agriculture and land use change (2.9 Tg N y^{-1}), waste (1.0 Tg N y^{-1}), and other anthropogenic sources (0.8 Tg N y^{-1}). Activities related to human food production (including land use change, industrial production of fertilizers and atmospheric formation of N_2O in NH_3 polluted air) are responsible for about 50% of the present global emissions

Table 3-7. Worldwide N_2O emissions in 1990 as derived from atmospheric N_2O and according to recent inventories

Source		N_2O emission (Tg N y^{-1})	References
Emissions derived from atmospheric N_2O (chapter 3.3):			
Natural		11.5 (8.0 - 14.0)	chapter 3.3.2
Anthropogenic		4.5 (3.9 - 5.1)	chapter 3.3.2
Total		16.0 (11.9 - 19.1)	
Recent inventories	*(chapter 3.4):*		
Natural		10.8 (8.1 - 13.7)	Table 3-3
Anthropogenic		6.1 (1.5 - 13.9)	Table 3-3
Total		16.9 (9.6 - 27.6)	

4 DUTCH N_2O EMISSIONS IN 1990: TWO METHODS

4.1 Introduction

The draft IPCC methodology (method I)
The Netherlands signed the "United Nations Framework Convention on Climate Change" (FCCC) in June 1992 at the "Earth Summit" in Rio de Janeiro. All parties to this convention commit themselves to (i) submit information about the quantities of greenhouse gases that they emit, by source, and about their national sinks, (ii) carry out national programmes for mitigating climate change and adapting to its effects, and (iii) support scientific and technical research and systematic observation related to the climate system, and promote the development and diffusion of relevant technologies.

It has been recognized that for international climate negotiations countries should report on greenhouse gas emissions in comparable ways. Internationally applicable "default" methods are therefore being developed by IPCC/OECD (1994) for national emission inventories. For N_2O a method has been proposed at an international workshop (Van Amstel, 1993). This method, described in 4.2, will hereafter be referred to as "method I" or the "IPCC method". Method I requires a reduced set of activity data, because in many countries statistics on human activities sich as industries and traffic are poor.

An update of the Dutch inventory (method II)
In the Netherlands reliable statistics are available, making it possible to estimate emissions in more detail than in method I. Moreover, for the Dutch situation some region-specific emission factors may be preferred. Therefore, in 4.3 an alternative method, referred to as "method II" is described. Method II is an update of the most recent inventory of Dutch nitrous oxide emissions, which was presented in *National Environmental Outlook 3* (RIVM, 1993a).

History of Dutch emission inventories
Between 1987 and 1993 the estimates of Dutch N_2O emissions have increased from 17 to 39.8 Gg N y^{-1} (or 27 to 63 Gg N_2O y^{-1}, Table 4-1). This is not a real increase, but a result of improved knowledge about sources of N_2O.

One of the first estimates, 17 Gg N y^{-1} for the year 1985, was presented in *Concern for Tomorrow* (RIVM, 1987). A few years later the fossil fuel source was downgraded and the biogenic source upgraded by Denier van der Gon and Swart (1990), who estimated total emissions to be 19 - 66 Gg N y^{-1}. This range was narrowed to 25.8 (14.4 - 36.8) Gg N for the years 1988-1990 by Van den Born et al. (1991), as also reported in *National Environmental Outlook 2*, with biogenic emissions from Bouwman and Van der Hoek (1991). The most recent estimate is 39.8 Gg N y^{-1} or 62.5 Gg N_2O y^{-1}, and has been reported in *National Environmental Outlook 3* (RIVM, 1993a). This inventory estimates abiogenic emissions substantially higher than Van den Born et al. (1991) due to revision of industrial emissions and the introduction of three-way catalysts in transport.

The method used for *National Environmental Outlook 3* is more complete than earlier methods, but the emission factors are largely based on studies from outside the Netherlands. Several measurement programs have recently started in the Netherlands. Method II uses the results to adapt the assumptions.

There are considerable uncertainties about the source strengths. Most emissions of nitrous oxide show large spatial and temporal variation. The number of available measurements differs per source and for some sources only a few data are available. The ranges given in methods I and II reflect realistic ranges as estimated by expert opinion, taking into account the experimental data available.

Table 4-1. Reported N_2O emissions from the Netherlands[1]

Reference		Dutch N_2O emissions (Gg N y^{-1})		
	Year	Biogenic	Abiogenic	Total
Concern for Tomorrow (RIVM, 1987)	1985	minor contributor	major contributor	17
Denier van der Gon and Swart (1990)	1985-90	<60	>9	19 - 66
Nat.Env.Outlook 2 (RIVM, 1991)[2]	1988-90	21.6 (12.6 - 30.2)[3]	4.2 (1.8 - 6.6)	25.8 (14.4 - 36.8)
Nat.Env.Outlook 3 (RIVM, 1993a)[4]	1990	25.5	14.3	39.8

[1] 1 Gg N_2O = 28/44 Gg N; Year reflects the year for which emissions were reported [2] Van den Born et al. (1991); [3] Based on Bouwman and Van der Hoek (1991); [4] See also Van Amstel et al. (1994)

4.2 Method I (IPCC methodology)

4.2.1 Description of method I

Method I, or the IPCC methodology, is an internationally applicable default method under development to quantify national anthropogenic N_2O emissions. The draft method used here is described in IPCC/OECD (1994) and was proposed during an international workshop, as reported by Mosier and Bouwman (1993) and Olivier (1993b). Tables 4-2 to 4-5 overview the emission factors used and the resulting Dutch 1990 emissions.

Method I

Energy: stationary combustion (Table 4-2)

N_2O Emission from stationary sources (g N_2O y^{-1}) = $\Sigma(EF_{abcd}$ x $Quantity_{abcd})$, where
EF = emission factor (g N_2O GJ^{-1}) (see Appendix 4-1)
Quantity = fuel input (GJ y^{-1})
a = fuel type
b = sector type
c = technology type
d = activity

Energy: mobile combustion (Table 4-3)

N_2O emissions from mobile combustion (g N_2O y^{-1}) = $\Sigma(EF_{abcd}$ x $Quantity_{abcd})$, where
EF = emission factor (g N_2O GJ^{-1} or g N_2O km^{-1} (see Appendix 4-1)
Quantity = amount of energy consumed (GJ y^{-1}) or distance travelled (km y^{-1}) x mean fuel consumption
a = transport mode (road, rail, air, water)
b = fuel type (diesel, gasoline, LPG, jet fuel, etc.)
c = vehicle type (passenger cas, light duty truck, heavy duty truck, bus)
d = emission controls and other factors

Industry (Table 4-4)

N_2O emissions from industrial sources (g N_2O y^{-1}) = $\Sigma(Activity_{ij}$ x $EF_{ij})$, where
EF = effective emission factor (g N_2O per kg product = kg N_2O per ton product) =
= EF_j x abatement $factor_j$
Activity = production level (ton of adipic acid or nitric acid produced)
i = total activity type
j = part of activities of type i with a specific applicable abatement factor
Abatement factor = 1 - percentage abated/100

Agriculture (Table 4-5)

N_2O emissions from agricultural soils (g N_2O y^{-1}) = $\Sigma(F_{mn} + F_{on} + F_{bnf})*C$, where
F_{mn} = amount of nitrogen fertilizer applied (g N y^{-1})
F_{on} = amount of organic nitrogen applied (animal manure or crop residue) (g N y^{-1})
F_{bnf} = amount of biological nitrogen fixation (g N y^{-1})
C = emission coefficient: 0.0040 (0.0015 - 0.0171) g N_2O per g N, or 0.0026 (0.0010 - 0.0109) g N_2O-N per g N, based on the 1990 global mix of nitrogen fertilizers used (Bouwman, pers.comm.); differs from the coefficients presented in Mosier and Bouwman (1993).

N_2O emissions from burning of savannas and agricultural wastes

The method relies on estimation of the gross CO_2 flux based on the amount of C in the biomass (the C/N ratio), and the efficiency of the burning. N_2O emissions are estimated as a ratio to nitrogen emitted.

Table 4-2. Method I (IPCC methodology): 1990 emissions of N_2O from stationary combustion in the Netherlands and Municipal Solid Waste (MSW) incineration

	Activity level[1]	Emission factor[2]	N_2O emission
Stationary combustion	PJ y^{-1}	g N_2O-N per GJ	Gg N_2O-N y^{-1}
- gas	1414	0.064 (0 - 0.700)	0.1 (0.0 - 1.0)
- oil	591	0.382 (0 - 1.782)	0.2 (0.0 - 1.1)
- coal	368	0.891 (0 - 6.364)	0.3 (0.0 - 2.3)
- other	91	n.q.	n.q.
- total	2464		0.6 (0.0 - 4.4)
Waste	10^3 ton y^{-1}	g N_2O-N per ton MSW	Gg N_2O-N y^{-1}
- MSW incineration	3400	19.1 (6.4-127.3)	0.1 (0.0 - 0.4)

[1] Albers et al. (1993); temperature corrected; excluding transportation and bunkers; including feedstocks; see Appendix 6-1; [2] IPCC emission factors (Olivier, 1993b); n.q. = not quantified.

Table 4-3. Method I (IPCC methodology): 1990 N_2O emissions from Dutch transport

Mobile combustion	Vehicle-km in 1990 (per millions years)[1]	Emission factors used (g N_2O km^{-1})[3]	N_2O emissions (Gg N y^{-1})
Passenger cars			
- gasoline	50519	0.064 (0.012-0.115)[4]	2.0 (0.4-3.7)
- diesel	15293	0.040 (0.020-0.060)	0.4 (0.2-0.6)
- LPG	14233	0.064 (0.012-0.115)[5]	0.6 (0.1-1.0)
Freight			
- low duty gasoline	1698	0.032 (0.004-0.060)[6]	<0.1 (0.0-0.1)
- low duty diesel	5551	0.040 (0.020-0.060)[7]	0.1 (0.1-0.2)
- low duty LPG	440	0.032 (0.004-0.060)[8]	<0.1 (<0.1)
- heavy duty trucks	3700	0.088 (0.044-0.132)[9]	0.2 (0.1-0.3)
- heavy duty trailers	2304	0.088 (0.044-0.132)[10]	0.1 (0.1-0.2)
Other			
- special vehicles gasoline[2]	48	0.032 (0.004-0.060)[11]	<0.1 (<0.1)
- special vehicles diesel[2]	307	0.088 (0.044-0.132)[12]	<0.1 (<0.1)
- busses	628	0.088 (0.044-0.132)[12]	<0.1 (0.0-0.1)
- motor cycles	1.955 (PJ)	11.75 (1.5-22) g/GJ[13]	<0.1 (<0.1)
- mopeds	1.264 (PJ)	11.75 (1.5-22) g/GJ[13]	<0.1 (<0.1)
Non-road (water and rail)	54.36 (PJ)	2 g/GJ[14]	0.1
Total			3.7 (1.0-6.3)

[1] Van Wee et al. (1993), Appendix 6-2; [2] These are commercial vehicles not equipped for good transport; [3] IPCC emission factors (Olivier, 1993b) using the average of the ranges presented; for emission factors in g N km^{-1} multiplied by 28/44; [4] Assuming for 1990: 64.9% + 12.7% of vehicle kilometers was driven in cars without emission control; 7% with a new closed loop 3-way catalyst; 15.5% with an aged closed loop 3-way catalyst (based on Baas, 1991); [5] as gasoline-fueled cars; [6] Assuming 100% km in cars without emission control; [7] As diesel passenger car; [8] As low duty gasoline; [9] 100% diesel; [10] As heavy duty trucks; [11] As low duty gasoline; [12] As heavy duty diesel; [13] In g N_2O GJ^{-1}; As uncontrolled gasoline passenger cars; [14] g N_2O GJ^{-1}; Based on heavy duty diesel trucks

Table 4-4. Method I (IPCC methodology): 1990 N_2O emissions from industry in the Netherlands

Industry	Production ($Gg\ N\ y^{-1}$)[1]	Emission factor ($g\ N_2O\text{-}N\ kg^{-1}$ product)[2]	Percentage abated globally (%)[2]	N_2O emission ($Gg\ N\ y^{-1}$)
Adipic acid production	0	191	32	0
Nitric acid production	617	17 (7 - 27)[3]	0	10.5 (4.3 - 16.7)
Total				10.5 (4.3 - 16.7)

[1] see Appendix 6-3; [2] Olivier (1993a,b); [3] 7 - 27 g N_2O-N per kg HNO_3-N = 2 - 9 g N_2O per kg HNO_3

Table 4-5. Method I (IPCC methodology); 1990 emissions of N_2O from Dutch agriculture

Agriculture	Nitrogen flux ($Gg\ N\ y^{-1}$)	Emission factor (%)[4]	N_2O emission ($Gg\ N\ y^{-1}$)
Synthetic nitrogen fertilizer	412[1]	0.26 (0.1 - 1.1)	1.1 (0.4 - 4.5)
Animal manure	507[2]	0.26 (0.1 - 1.1)	1.3 (0.5 - 5.5)
Biological N_2 fixation	15[3]	0.26 (0.1 - 1.1)	0.0 (0.0 - 0.2)
Total	934		2.4 (0.9 - 10.2)

[1] Van der Hoek (1994); [2] 148 Gg N produced in meadow + 359 Gg N used on Dutch soil (Van der Hoek, 1994, pers.comm.; see also Table A-12 in Appendix 6-4); [3] RIVM (1993a); [4] calculated from the 1990 global fertilizer mix used (Bouwman, pers.comm.); differs from Mosier and Bouwman (1993)

4.2.2. Dutch 1990 emissions from all sources (method I).

Method I yields anthropogenic N_2O emissions of 17.3 (6.3 - 38.0) Gg N y^{-1}, with industries as major contributor (Table 4-6). The IPCC methodology is still in development. Several sources of N_2O are not included, as will be shown in 4.3. In addition, the IPCC emission factors for transport and agriculture are a matter of discussion. For transport the IPCC methodology does not provide emission factors which are typical for Europe. Therefore, the averages of the IPCC ranges presented by Olivier (1993b) are tentatively used here.

Table 4-6. Method I (IPCC methodology): 1990 N_2O emissions in Gg N y^{-1}in the Netherlands

Source	N_2O emissions
Energy	
- stationary combustion[1]	0.6 (0.0 - 4.4)
- mobile combustion[2]	3.7 (1.0 - 6.3)
Industry[3]	
- nitric acid production	10.5 (4.3 - 16.7)
- adipic acid production	0.0
Agriculture[4]	
- nitrogen fertilizer	1.1 (0.4 - 4.5)
- manure	1.3 (0.5 - 5.5)
- biological N_2 fixtion	<0.1 (0.0 - 0.2)
Waste[1]	
- waste incineration	0.1 (0.0 - 0.4)
Total	17.3 (6.3 - 38.0)

[1] Table 4-2; [2] Table 4-3; [3] Table 4-4; [4] Table 4-5

4.3 Method II (update of the Dutch *National Environmental Outlook 3*)

Method II is an update of the methodology in *National Environmental Outlook 3* (RIVM, 1993a; Van Amstel et al., 1994). For some sources, it is similar to the IPCC method (Method I). For others an alternative method is proposed. The methodologies for biogenic and abiogenic emissions are described in 4.3.1.1 and 4.3.1.2. For each of the contributing sectors an overview of emissions is given in 4.3.2.1 to 4.3.2.7.

4.3.1 Description of method II

4.3.1.1 Biogenic emissions in method II

In method II a distinction is made between natural and anthropogenic biogenic emissions of N_2O. Anthropogenic emissions include enhanced background emissions and emissions induced by annual N inputs. Thus the follwing emissions are distinguished:
- *Natural emissions.* Natural biogenic emissions are defined as biogenic emissions from the natural terrestrial and aquatic ecosystems in the preagricultural era, including (i) biogenic soil emissions and (ii) biogenic emissions from aquatic systems.
- *Enhanced background emissions.* The anthropogenic background emission is the difference between the current background emission and the historic natural emission. The current background emission is different from the natural emission as a result of the conversion of natural ecosystems to agriculture and other uses, by changes in the hydrology and by effects of long-term fertilizer use. The increased background emission does not include the effect of annual N inputs. It is estimated for organic soils by accounting for the lowering of the groundwater table and changes in soil nitrogen caused by long-term fertilizer application. For mineral soils the background emission is enhanced mainly as a result of long-term fertilizer use. As there are no estimates for the natural emissions from aquatic systems, the increased background emission is assumed to be negligible.
- *Emissions induced by annual N inputs.* Starting from the background N_2O emission, additional N_2O release occurs as a result af annual inputs of N to soils and aquatic systems.

Biogenic emissions in method II:

$$N_2O_{\text{biogenic}} = N_2O_{\text{biogenic, natural}} + N_2O_{\text{anthropogenic backround}} + N_2O_{\text{N input}}$$

$$N_2O_{\text{anthropogenic background}} = N_2O_{\text{current background}} - N_2O_{\text{biogenic, natural}}$$

$$N_2O_{\text{N input}} = \sum_{i=1}^{m} (\text{N INPUT})_i \times EF_i$$

where

N_2O_{biogenic} = biogenically produced N_2O (Gg N y^{-1})
$N_2O_{\text{biogenic, natural}}$ = natural part of biogenic background emissions (Gg N y^{-1})
$N_2O_{\text{anthropogenic background}}$ = anthropogenic part of biogenic background emissions (Gg N y^{-1})
$N_2O_{\text{current background}}$ = present-day biogenic background emissions (Gg N y^{-1})
$N_2O_{\text{N input}}$ = biogenic emissions induced by anthropogenic N fluxes (Gg N y^{-1})
$(\text{N INPUT})_i$ = anthropogenic nitrogen flux of type i (Gg N y^{-1})
EF_i = Emission Factor (kg N_2O-N per kg N INPUT) for a flux of type i
i = type of N-flux or soil
m = number of distinguished N fluxes (to soils, waters, etcetera)

(1) Natural biogenic emissions in method II

Natural emissions are emissions that are not induced by human activities, and include (i) biogenic soil emissions and (ii) biogenic emissions from surface waters.

- *Soils.* Natural N_2O emissions from the Dutch land area are not easily determined, the present land cover in the Netherlands being all virtually determined by human influences: without human influences the Dutch land area would have been much smaller than it is today. Bouwman and Van der Hoek (1991), in their "global approach", use the model described by Bouwman et al. (1993). They used the model to calculate soil emissions for the current land cover on a 1° x 1° grid. For large world regions, where the natural vegetation has not been removed, the model calculates natural soil emissions. For soils where the natural vegetation has been replaced by arable lands or grassland, the calculated emission rather reflects current background emissions. For Dutch soils under the present land cover the model calculates emissions of 1.5 Gg N y^{-1} (Table 4-7). These calculations do not take into account the lowering of the groundwater table and long-term use of fertilizers, inputs of animal excreta and atmospheric deposition. These model results may therefore be close to the natural part of biogenic N_2O emission from Dutch soils. Therefore in method II it is assumed that natural, biogenic soil emissions equal 1.5 Gg N y^{-1}, and may range from 0.5 to 3.0 Gg N y^{-1} (Table 4-8). This may be an overestimation for natural soil emissions, because the present land area has been enlarged by poldering.
- *Surface waters.* Natural emissions from surface waters cannot be quantified at present, but are presumably small.

Table 4-7. Background N_2O emissions from Dutch soils according to Bouwman and Van der Hoek (1991)

Soil type	Area (1000 ha)	N_2O emissions per hectare (kg N ha^{-1} yr^{-1})	N_2O emission (Gg N y^{-1})
Arable land	931	0.52	0.5
Grassland	1081	0.50	0.5
Forests	300	0.42	0.2
Other lands	1080	0.30	0.3
Total	3392	0.43	1.5

(2) Anthropogenic biogenic emission in method II: background emissions

- *Current backround emissions from soils.* In the second approach of Bouwman and Van der Hoek (1991) ("country" approach) it is recognized that background emissions from organic soils are enhanced by anthropogenic lowering of the groundwater table. The emission factors (in kg N ha^{-1} y^{-1}) used are based on measured fluxes outside the Netherlands. Method II modifies these emission factors based on recent Dutch research. Velthof and Oenema (1994a) observed that N_2O background emissions from grassland on organic Dutch soils are indeed relatively high, but lower than the 27.5 kg N ha^{-1} y^{-1} as estimated by Bouwman and Van der Hoek (1991). Method II uses 10 (1 - 20) kg N ha^{-1} y^{-1} for calculating total background emissions from grassland on organic soils (Table 4-8). The emission factors for grassland on mineral soils and arable land are 1 kg N ha^{-1} y^{-1} from Bouwman (1994), ranging from 0.5 to 5 kg N ha^{-1} y^{-1}. The total current background emission from organic and mineral soils is estimated at 4.5 (1.1 - 14.1) Gg N y^{-1} (Table 4-8). As the natural part is 1.5 Gg N y^{-1}, the anthropogenic increase is 3.0 Gg N y^{-1}.
- *Surface waters.* It is assumed here that background emissions from surface waters are not enhanced by human activities.
- *Global warming.* Background emissions may further increase in the future when the temperature rises as a result of enhancement of the greenhouse effect. It is assumed here that present Dutch background emissions are not yet influenced by climate change.

Table 4-8. Method II: current biogenic background emissions in 1990 in the Netherlands, and the anthropogenic and natural contribution to the total

	Area (1000 ha)	Emission factor (kg N ha^{-1} y^{-1})	N_2O emission (Gg N y^{-1})
Grasslands on organic soils	274	10 (1 - 20)[1]	2.7 (0.3 - 5.5)
Grasslands on mineral soils	822	1.0 (0.5 - 5)[2]	0.8 (0.4 - 4.1)
Arable land	908	1.0 (0.5 - 5)[2]	0.9 (0.5 - 4.6)
Total[3]			4.5 (1.1 -14.1)
Natural[4]			1.5 (0.5 - 3.0)
Anthropogenic[5]			3.0 (0.6 - 11.1)

[1] see text; [2] Bouwman (1994); [3] Aquatic emissions are not quantified; [4] Table 4-7, background emissions from waters are unknown; [5] calculated as the difference between total and natural background emission

(3) Anthropogenic biogenic emissions in method II: induced by N input

Starting from the background N_2O emissions, additional biogenic emissions occur as a result of annual inputs of N to soils and aquatic systems. N_2O emissions induced by anthropogenic nitrogen fluxes are, like in method I, calculated as a fraction of the N input. Method II uses several classes of emission factors, instead of one emission factor for all situations as proposed in method I. Four classes of emission factors are distinguished (Table 4-9). Class 2, 0.2 - 1.25%, is closest to the IPCC range used in method I (0.1 - 1.1%). For some nitrogen fluxes N_2O emissions may be less than 0.2% (class 1), or more than 1.25% (class 3 and 4). Whether emissions are at the lower or higher end of the range of a certain class may be determined by such "risk factors" as timing and frequency of fertilizer application (Table 4-10). The sources of nitrogen considered are (i) synthetic nitrogen fertilizer, (ii) animal manure, (iii) atmospheric deposition of NOx and NHx, (iv) biological N_2 fixation, (v) nitrogen loading to surface waters, (vi) sewage treatment, and (vii) landfills.

(i) Synthetic nitrogen fertilizer
For synthetic nitrogen fertilizers, classes 2 and 3 are used in method II (Table 4-9), assuming that 0.2 - 2.5% of the fertilizer nitrogen (corrected for NH_3 emissions, see Appendix 6-4) applied is emitted as N_2O (Bouwman, 1994). This is close to the emission factors used for *National Environmental Outlook 3* (RIVM, 1993a; Van Amstel et al., 1994), and reviews of available literature (Eichner, 1990; Mosier, 1993). The total range of classes 2 and 3 is in agreement with Bouwman (1994), who analyzed studies in which fertilizer-induced fluxes of N_2O were measured for a full year. The upper limit of the Class 2 range is the mean of 1.25% estimated by Bouwman (1994).

Soil emissions of N_2O show large spatial and temporal variation, which makes it difficult to distinguish situations with higher or lower emissions. Nevertheless method II assumes for Dutch emissions that emissions from organic soils are higher than those from mineral soils, because in general, organic soils have higher denitrification potentials, and therefore potentially higher N_2O production, than mineral soils. In a monitoring study emissions of N_2O from Dutch grassland soils were observed for two years (Velthof and Oenema, 1994a and in Slanina et al., in prep.). In mineral soils 1% of the N on surface applied as calcium ammonium nitrate was emitted as N_2O, and in organic soils 2 - 4%. Therefore, for surface application of fertilizers class 2 is used for mineral soils, and class 3 for organic (Table 4-9). This includes fertilizers used in horticulture. No distinction is made between grassland, arable land or other type of lands.

Several studies indicate that the type of fertilizer could also be a factor of importance. In method II the type of fertilizer is, however, not considered, because its general effects are uncertain (Mosier, 1993, 1994; Bouwman, 1994). Also emissions from greenhouse horticulture are not considered seperately, because of lack of data.

Factors determining whether emission factors are at the higher or lower end of the range may include timing and frequency of application. Wetting after application may promote N_2O production (Letey et al., 1981). And frequent application of relatively small amounts of fertilizer may, if weather conditions are similar, result in less N_2O production than less frequent application of high doses.

(ii) Animal manure

Manure-induced N_2O emissions can take place in meadows, in stables, and after use of manure as fertilizer. The manure N from which N_2O emissions are calculated are all corrected for NH_3 emissions.

- *Urine patches and faeces in meadows.* Faeces and urine production in meadows may enhance biogenic soil emissions of N_2O. Velthof and Oenema (1994a, and in Slanina et al., in prep.) found that N_2O emissions from grassland grazed by cattle were 1.5 to 6 times as high as emissions from ungrazed land (N-fertilized grassland soils in the Netherlands). N_2O emissions are enhanced as a result of extra nitrogen input as faeces and urine, but possibly also by trading. They concluded that 1 - 8% of the N in faeces and urine is converted to N_2O (in Slanina et al., in prep.). Most of this N_2O may be from urine patches (Van Faassen, 1993).

Urine-patches show in general high emissions of N_2O, because of the high concentrations of NH_4^+, increased moisture content and high pH (Van Faassen, 1993). A proposed mechanism for the high N_2O production is an increase of NH_3 concentrations and pH after urea hydrolisis, by which NO_2^- oxidation to NO_3^- in nitrification is slowed down. When in addition oxygen levels decrease locally, for instance, as a result of the increased moisture content in urine spots, nitrite can be used as terminal electron acceptor in denitrification and converted into N_2O. As long as nitrate and nitrite levels are high, reduction of N_2O to N_2 is slowed down (Van Faassen, 1993; Monaghan and Barraclough, 1993; Dendooven et al., 1994). In addition, nitrifiers may produce N_2O in urine-patches. The key process leading to high N_2O emissions may be accumulation of nitrite (NO_2^-). This can also occur after injection of NH_3-containing fertilizers and in deep litter stables.

Indeed, the observed N_2O losses from urine patches are high. De Klein (1994) observed that N_2O 8 - 16% of the urine-N was lost as N_2O within 14 days after application to Dutch sandy grassland soils.

Velthof and Oenema (1994b) reported N_2O emissions from urine patches in mineral soils which were per cm^2 up to 200 times as large as from surrounding soil. The observed N_2O fluxes equalled 0.5% of the urine nitrogen input, which was 10 times as large as the flux induced by synthetic fertilizer. All observed emissions were considered low in this experiment, due to dry and cold weather conditions (Velthof and Oenema, 1994b).

Laboratory experiments also showed high fluxes of N_2O from urine patches: the observed N_2O-N fluxes from undisturbed cores of grassland on mineral soil were at least 0.1 - 0.8% of the added urine N (Van Faassen, pers.comm., and in Slanina et al., in prep.). These percentages were considered the lower limit of the range of N_2O produced during 60 days. Actual emissions may be higher for at least two reasons: (i) urine patches are known to show enhanced nitrate concentrations for months, so that N_2O emissions may also be enhanced for a long time, and (ii) the observed fluxes were from mineral soils, while N_2O emissions from organic soils are usually higher.

Summarizing, the N_2O flux from urine patches in grazed grasslands may exceed class 2. The N_2O emissions induced by faeces-N are less well known, but probably not as high as those induced by urine N. The N content of faeces is lower than that of urine, and most of the faeces N is organic, which comes available gradually. Method II therefore uses class 3 for urine (1.25 - 2.5%) and class 2 for faeces (0.2 - 1.25%) for all livestock (Table 4-9). No difference between soil types is considered here because of lack of data.

- *Stables.* When produced in stables, urine and manure are often mixed, stored for a while, and consecutively applied to soils as fertilizer. Emissions of N_2O from animal waste in stables or during storage may vary. Liquid and most solid manure becomes anoxic during storage. Anaerobic storage of manure may not result in large amounts of N_2O, since during permanent anaerobiosis nitrification is inhibited (Oenema et al., 1993). As a result, nitrate availability is low, and therefore denitrification is low. The lowest emission class 1 (<0.2%) is used in method II for anaerobic storage of liquid and solid maure.

In deep-litter stables manure is stored aerobically, so that nitrification proceeds well. High N_2O emissions were observed in deep-litter stables, possibly as a result of the same mechanism as in urine patches. Emission class 4 (>2.5%) is used for these stables, based on Groenesteijn et al. (1993). Deep-litter stables are as yet not current practice in the Netherlands.

A proposed mechanism to reduce NH_3 emissions from manure is the addition of HNO_3. This is no current practice in the Netherlands. Oenema and Velthof (1993) and Velthof and Oenema (1993) showed that this may increase N_2O emissions during storage and after application to soils. Emission of N_2O depends on the pH of the slurry. In general, emissions are much higher at a pH of 6 than at a pH lower than 4.5. Application of nitric acid during storage of manure is meant to lower the pH to 4 - 4.5. However, once denitrification starts the pH could locally increase, leading to N_2O emissions. Application of nitric acid shortly before application, typically lowers the pH to 6. In method II, *additional* N_2O emissions after addition of HNO_3 are calculated using class 4 emission factors (> 2.5%) for the HNO_3 added to manure. The added HNO_3 is usually regarded as a synthetic fertilizer, so that these additional emissions could be compared to those induced by synthetic fertilizers.

Most veal calf manure in the Netherlands is biologically treated, during which about 95% of the nitrogen is removed by nitrification and denitrification (Willers et al., 1993). The related N_2O emissions may exceed class 2: in sewage treatment plants up to 11% of the denitrified nitrogen may be emitted as N_2O (Hong et al., 1993). Class 3 is used in method II for biological treatment of all kinds of manure.

- *Manure used as fertilizer.* N_2O soil emissions due to the use of manure as fertilizer are, in general, within the same range as these due to the use of synthetic fertilizers (Bouwman, 1994). Therefore manure-induced N_2O emissions are calculated as for synthetic fertilizers: class 2 for surface application on mineral soils and class 3 for surface application on organic soils.

In addition, it is assumed that injection gives rise to higher N_2O emissions than surface application. It has been observed that injection of the synthetic fertilizer anhydrous NH_3 gives rise to higher emissions than surface application of fertilizers, and that N_2O emissions increase with injection depth (Breitenbeck and Bremner, 1986a,b). Increased denitrification and/or increased N_2O emissions as a result of injection of manure has been observed by Thompson et al. (1987), Comfort et al. (1990), and Petersen (1992). After injection of manure, conditions resemble those in urine spots (see above). Thus hydrolysis of urea may increase NO_2^- availability, which in turn may be reduced to N_2O in denitrification (Monaghan and Barraclough, 1993; Dendooven et al., 1994). It is therefore assumed here that injection of manure gives rise to higher N_2O emissions than surface application: method II uses class 3 for manure injected or otherwise placed *in* the soil

(Table 4-9). These factors are used for all types of manure. No distinction is made between types of soil in this respect.

For synthetic fertilizers other than NH_3 the effects of injection on N_2O emissions are less clear and experiments scarce (Granli and Bockman, 1994). Some studies indicate that injection instead of surface application of synthetic fertilizers other than NH_3 may in fact decrease N_2O emissions, because during soil transport some N_2O may be reduced to N_2. Thus it could be that injection only increases N_2O emissions from animal manure and anydrous NH_3.

(iii) N_2O emissions induced by atmospheric deposition of NOx and NHx

Atmospheric deposition of nitrate (NO_3^-) and ammonium (NH_4^+) may increase biogenic N_2O production in soils and waters as a result of increased nitrification and denitrification. Nitrate and ammonium deposition result from emissions of NOx and NH_3. NOx (NO and NO_2) comes from fossil fuel combustion and traffic mainly, and NH_3 from agriculture. In the troposphere NOx and NH_3 are transported over long distances before deposition.

In method II, N_2O emissions induced by atmospheric deposition are estimated as 0.2 - 1.25% (Class 2) of the NOx-N and NH_3-N *emissions* in the Netherlands. Use of *deposition* rates instead of emissions would lead to an underestimation of N_2O emissions due to Dutch human activities, since a major part of Dutch NOx and NH_3 emissions are deposited elsewhere (Table 4-11). Therefore, there is a case to estimate a country's N_2O emissions from its NOx and NH_3 *emissions*, as was also done in the *National Environmental Outlook 3*. This results in an estimated N_2O release of 3.5 Gg N y^{-1}, which exceeds the estimate resulting from deposition rates by a factor of 2 (Table 4-11).

Class 2 emission factors are used, because atmospheric deposition of nitrate and ammonium can be regarded as surface application of synthetic nitrogen fertilizer on agricultural soils. Most of the NH_3 and NOx emitted in the Netherlands is deposited onto agricultural land; the Dutch land area is largely agricultural, and so is a considerable part of the area surrounding the Netherlands. Moreover, class 2 is in agreement with observed fluxes outside the Netherlands (Bowden et al., 1991; Brumme and Beese, 1992).

(iv) Biological N_2 fixation

Legumes such as clover and alfalfa live in symbiosis with bacteria, which are able to use atmospheric N_2 as a source of nitrogen. Growing legumes on agricultural fields is an alternative for nitrogen fertilization. Since legumes increase the mineral nitrogen content of soils, they stimulate N_2O production. In *National Environmental Outlook 3* these N_2O emissions are estimated to be 3 ± 1 kg N_2O-N ha^{-1} y^{-1} (Bouwman and Van der Hoek, 1991; Van Amstel et al., 1994; RIVM, 1993a). An alternative for this method is relating N_2O emissions to the nitrogen fixation rate, as proposed in method I. Class 2 is closest to the IPCC range (method I), and adopted in method II.

(v) Leaching and run-off; nitrogen loading to surface waters

Nitrogen applied to soils as fertilizers may leach from the soil or run-off. This is one of the most important sources of nitrogen in Dutch surface waters. Other anthropogenic sources may be sewage, or effluent of sewage treatment plants, and industries. Nitrogen enrichment enhances biogenic N_2O production. Similar to deposition-induced emissions, the Dutch nitrogen input in aquatic systems are accounted for irrespective of the place where emissions occur. In *National Evironmental Outlook 3* it is assumed that 2.7% (2 - 3.9)% of the nitrogen input into Dutch waters is emitted as N_2O. Bouwman and Van der Hoek (1991) considered this an upper limit. Method II uses a lower emission factor, based on Seitzinger (1988; 1990). Seitzinger (1988) found that in general less than 0.5% of denitrified N is emitted as N_2O, although from heavily polluted sediments N_2O emissions may be as high as 6%. In estuaria about half of the N input is denitrified (Seitzinger, 1990), which may also hold for rivers. It is therefore unlikely that N_2O emissions from surface waters exceed 1.25% of the N input, except when the N loading is extremely high. Emissions of N_2O from Dutch surface waters are calculated in method II using class 2 emission factors.

(vi) Sewage treatment plants

In sewage treatment plants nitrogen is removed from waste by denitrification. Nitrogen enters the plant mostly as NH_4^+. During the treatment process conditions that favor nitrification and denitrification alternate. As a result, the ammonium is nitrified to nitrate, which is consecutively denitrified to N_2 or N_2O. Production of N_2O can occur during nitrification and denitrification. Denitrification may be the major source (Debruyn et al., 1994). Reported N_2O emissions range from 0.1 to 6% of the nitrogen in influent (Nogita et al., 1981; BKH, 1994), or up to 11% of the denitrified nitrogen (Hong et al., 1993).

Method II uses class 2 (0.2 - 1.25% of N removal) for sewage treatment plants, based mainly on BKH (1994). This is much lower than the class 4 emission factors used in *National Environmental Outlook 3* (RIVM, 1993a). BKH (1994) concluded from the literature that in nitrification 0.3% of the nitrogen in the N influent which does not end up in sludge is emitted as N_2O, and that in denitrification 0.3% of the available NO_3^- is emitted as N_2O. In addition, BKH estimates that 1% of the sludge N is emitted as N_2O when the sludge is applied to soils, and 1% of the N in effluent after entering, for instance rivers. In the Netherlands sludge contains 17.5% of the influent N, and 51% of the influent N is nitrified to NO_3^- (BKH, 1994). This means that according to the BHK methodology 0.4% (0.003 * 82.5 + 0.003 * 51) of the influent N is emitted as N_2O from sewage treatment plants, and another 0.2% (0.01 * 17.5) from sludge (assuming that eventually most sludge N is subject to nitrification and denitrification). Emissions from effluent are included in emissions from surface waters in method II.

(vii) Landfills and organic wastes

The N_2O production due to organic wastes is poorly known. Organic waste contains nitrogen, which may be mineralized in landfills. This may be considered an nitrogen input into soils. Since no studies are available on this source, class 2 could be tentatively used. From the year 1995 on a minimum of organic wastes will be dumped in landfills in the Netherlands. This source may therefore decline within the coming years. On the other hand, emissions from composting may increase. Also agricultural wastes, which are left on the fields, contribute to the N content of soil and therefore to N_2O production.

Table 4-9. Method II emission factors for biogenic N_2O emissions induced by N input

Emission factor class	N INPUT[2]	Contributing sector
Class 1: <0.2% of N flux	- anaerobic storage of liquid and solid manure	agriculture
Class 2: 0.2-1.25% of N flux	- synthetic fertilizer on mineral soil[1]	agriculture
	- surface application of manure as fertizer on mineral soil[1]	agriculture
	- faeces produced in meadow[1]	agriculture
	- atmospheric deposition of NOx and NH_3	agriculture/energy
	- biological N_2 fixation (legumes)	agriculture
	- nitrogen leaching/run-off	agriculture
	- other nitrogen loading surface waters	industry/waste/energy
	- landfills (composting)	waste
	- nitrogen removal in sewage treatment plants	waste
Class 3: 1.25-2.5% of N flux	- synthetic fertilizer on organic soil[1]	agriculture
	- surface application of manure as fertilizer on organic soil[1]	agriculture
	- injection of manure as fertilizer[1]	agriculture
	- urine patches[1]	agriculture
	- biological treatment of veal calf manure	agriculture
Class 4: > 2.5% of N flux	- nitric acid (HNO_3-N) added to manure[3]	agriculture
	- deep litter stable or other aerobic storage of manure[1]	agriculture

[1] Excluding NH_3-N emissions; [2] Anthropogenic N flux to soils, waters, etc.; [3] Additional emissions of N_2O induced by HNO_3-N; to be added to the manure-N induced emissions

Table 4-10. Situations of higher and lower potentials for N_2O emissions[1]

Variable	High emission potential	Low emission potential
Soil type	Organic soils	Mineral soils
Soil moisture content	Moist soil	Dry soil
Irrigation/rainfall	Wetting and drying of soil	Constant (low) moisture
Fertilizer N	High application rate, low frequency	Low rate, high frequency

[1] these could be used to determine whether emission factors at the high or low end of the range of an emission class are to be preferred. In the present study the emission factors are tentatively estimated within the range of possibilities, not taking into account the information in this table.

Table 4-11. Dutch emissions and deposition of NOx and NHx in 1990

	Emission from the Netherlands (Gg N y^{-1})	Deposition on Dutch area (Gg N y^{-1})	Net export[2] (% of emission)
NOx	175[1]	49[1]	72%
NHx	177[1]	109[1]	38%
Total (NOx + NHx)	352	158	55%
Related N_2O emissions (as 1% of N flux)	3.5	1.6	

[1] Van der Hoek (1994), Appendix 6-7, RIVM (1993a); [2] (emission - deposition)/emission * 100%

4.3.1.2 Abiogenic emissions in method II

Natural abiogenic emissions

Abiogenic N_2O formation occurs in the troposphere and soils. Abiogenic N_2O formation in soils (chemodenitrification) is often biologically induced, and therefore included in biogenic emissions (4.4.1.1).
- *Atmospheric formation.* Atmospheric formation in the troposphere is tentatively estimated in method II. Three mechanisms of N_2O formation in the troposphere are described in the literature (2.4). For only one of these three has the source strength been quantified (Dentener, 1993). Dentener calculated that globally 1.3% of the nitrogen emitted as NH_3 is oxidized to N_2O. At mid-latitudes this percentage is lower as a result of lower OH concentrations. In the grid cell covering the Netherlands, N_2O production equals 0.01 (0 - 0.05)% of the NH_3-N emissions (Dentener, pers.comm.). It is assumed that 10% hereof is natural and 90% anthropogenic (Table 4-12).

Anthropogenic abiogenic emissions

Nitrous oxide can be formed abiogenically in combustion processes, industries and in polluted atmosphere. Method II calculates N_2O emissions from combustion and industries as activity level x emission factor (Table 4-12).
- *Stationary combustion.* The method for stationary combustion as proposed by IPCC (method I) is the same as used in *National Environmental Outlook 3* and adopted here for method II (Tables 4-2 and 4-12). The only exception is the emission factor for Fluidized Bed Combustion (FBC), which is taken from Spoelstra (1993). The other emission factors are from De Soete (1993), and based on measurements in 95 power plants outside the Netherlands. In a limited number of Dutch power plants lower (around ambient) concentrations were observed (Spoelstra 1993; Van Bergen et al., 1991). These results were in within the range of measurements as published by De Soete (1993). Nevertheless, in method II the conclusion of Spoelstra (1993) that N_2O emissions from conventional power plants are negligible is not adopted, because the concentrations measured by Spoelstra were at the lower end of the detection limit, so that it is difficult to determine whether emissions were zero or low. In method II therefore the emission factors of De Soete (1993) are used.
- *Mobile combustion.* For mobile combustion the emission factors of Baas (1991) are used in method II, which differ from the IPCC emission factors (Table 4-3). The study by Baas (1991) is preferred because (i) the IPCC emission factor are tentative, and (ii) because Baas tried to estimate emission factors applicable to European vehicles, while the IPCC emission factors are largely based on data from the USA. In the USA cars and driving behavior are different than in Europe, which affects the formation of N_2O. New measurements by Baas (1994) generally confirm the ranges used here.

- *Industry.* Method II adopts the emission factors for nitric acid and adipic acid production from method I (Table 4-4). Adipic acid is not produced in the Netherlands.

The emission factors for nitric acid are based on measurements in plants outside the Netherlands, where the observed N_2O concentrations ranged from 287 to 1700 ppmv (De Soete, 1993). At present there are no measurements of N_2O in Dutch nitric acid plants available, but data may become available in 1995 and 1996 (e.g. HAS, 1994; Van Der Meer, pers.comm.). Despite lack of direct measurements, there are indications that exhaust gases of Dutch plants the N_2O concentrations largely exceed 200 g N_2O per m^3, or 100 ppmv (Van Der Meer, pers.comm.). The N_2O is formed during oxidation of NH_3 (see 3.2.2), which is a usual step in nitric acid production. The actual amount of N_2O emitted can be affected by, for instance, NOx reduction techniques. As long as no measurements are available from Dutch plants, it seems reasonable to use the method I emission factors.

Emissions of 1.1 Gg N_2O-N y^{-1} from other chemical industries have been reported to the Dutch emission registration (VROM, 1993). This emission may be from production of caprolactam (RIVM, 1993a), but the exact origin of the source needs further research.

- *Municipal waste incineration.* For waste incineration an emission factor of Spoelstra (1993) is used in method II, this factor being derived from a Dutch incinerator (12.7 g N_2O-N per ton). The upper limit of the range (127 g N_2O-N per ton) is taken from method I (Table 4-2). The lower limit (3.2 g N_2O-N per ton) is from recent measurements in two Dutch incinerators, both of which showed low N_2O concentrations (Oonk, unpublished results).
- *Atmospheric formation.* As described for abiogenic natural emissions, N_2O formation is estimated as 0.01 (0 - 0.05)% of the NH_3-N emitted, of which 90% anthropogenic (Dentener, pers.comm.).
- *Anaesthesia.* It is assumed here that the annual use of nitrous oxide reflects the annual emissions.

Table 4-12. Method II emission factors for abiogenic processes

	Method II emission factor[1]	Remark
Natural emissions		
- atmospheric formation	0.001 (<0.005)% g NH_3-N emitted	Dentener (pers.comm.)
Anthropogenic emissions		
Energy: stationary combustion		
- gas	0.064 (0-0.700) g N_2O-N GJ^{-1}	as method I (Table 4-2)
- oil	0.382 (0-1.782) g N_2O-N GJ^{-1}	as method I (Table 4-2)
- coal; non-FBC	0.891 (0-6.364) g N_2O-N GJ^{-1}	as method I (Table 4-2)
- coal; FBC	26.7 (4.4 - 49) g N_2O-N GJ^{-1}	Spoelstra (1993)
Energy: mobile combustion		
passenger vehicles:		
- gasoline no control	0.015 (0.004-0.060) g N_2O km^{-1}	Baas (1991)
- gasoline new 3-way catalyst	0.035 (0.020-0.250) g N_2O km^{-1}	
- gasoline old 3-way catalyst	0.120 (0.110-0.320) g N_2O km^{-1}	
- diesel	0.031 (0.030-0.040) g N_2O km^{-1}	
freight:		
- low duty gasoline	0.045 (0.004-0.060)[2] g N_2O km^{-1}	
- heavy duty diesel	0.200 (0.029-0.840) g N_2O km^{-1}	
Industry		
- nitric acid production	17 (7-27) g N_2O-N per kg HNO_3-N	as method I (Tabel 4-4)
- adipic acid production	191 g N_2O-N per kg AA	as method I (Table 4-4)
- other chemical industry	1.1 Gg N_2O-N y^{-1}	Dutch emission registration
Waste		
- municipal solid waste incineration	12.7 (3.2-127) g N_2O-N per ton	Spoelstra (1993) and Table 4-2
Other		
- atmospheric formation	0.009 (<0.045)% g NH_3-N emitted	Dentener (pers.comm.)
- anaesthesia	use = emission	

[1] In g N_2O-N per activity; for mobile combustion in g N_2O per activity (1 g N_2O = 28/44 g N); [2] Range as passenger vehicles (gasoline without catalyst)

4.3.2 Dutch 1990 emissions per sector

4.3.2.1 Natural emissions

Natural emissions from the Netherlands are tentatively estimated here to be 1.5 (0.5 - 3.3) Gg N y^{-1} (Tables 4-8 and 4-13). The natural part of background emissions from soils is estimated at 1.5 (0.3 - 3.0) Gg N y^{-1}. The natural part of atmospheric formation is estimated at <0.1 Gg N y^{-1}.

Table 4-13. Method II; natural emissions from the Netherlands; n.e. not estimated

Source	N_2O emission (Gg N y^{-1})
Biogenic	
- soils	1.5 (0.5 - 3.0)[1]
- waters	n.e.
Abiogenic	
- atmosphere	<0.1 (0 - <0.1)[2]
Total	1.5 (0.5 - 3.0)

[1] Table 4-8; [2] Table 4-12; total NH_3 emission in the Netherlands is 177 Gg N y^{-1} (Van der Hoek, 1994; Appendix 6-7).

4.3.2.2 Energy (stationary and mobile combustion)

Total emissions from combustion processes

Nitrous oxide emissions from energy use in the Netherlands are 5.4 (1.8 - 17.5) Gg N y^{-1}. This is 14% of Dutch emissions. Abouth two-thirds of these emissions are direct emissions from mobile combustion. Stationary combustion and atmospheric deposition of NOx contribute 13, and 23%, respectively.

Stationary combustion

Dutch 1990 emissions from stationary combustion are 0.7 (0.0 - 4.5) Gg N y^{-1} (Table 4-14). These emissions are abiogenic and do not include N_2O formation in NOx polluted air, or biogenic emissions due to atmospheric deposition of NOx. Although fluidized bed combustors only accounts for less tha 1% of the fossil fuels used, they contribute to 6% of the total Dutch emissions from stationary combustion.

Mobile combustion

Using the emission factors of Baas (1991) Dutch 1990 emissions amount to 3.4 (1.5 - 11.5) Gg N y^{-1} (Table 4-15). These emissions do not include N_2O emissions due to NOx. About 50% of the emissions come from passenger cars.

NOx deposition

Biogenic emissions as a result of NOx deposition is calculated here as 1 (0.2 - 1.25)% of the NOx emitted in the Netherlands, or 1.2 (0.2 - 1.5) Gg N y^{-1} (Table 4-16). Formation of N_2O in NOx polluted troposphere is included in the category "other" (4.3.2.7), because this formation is influenced by NH_3 emissions from agriculture.

Table 4-14. Method II; Dutch 1990 activity levels, emission factors and emissions of N_2O from stationary combustion

Stationary combustion	Energy use (PJ y^{-1})[1]	Emission factor (g N_2O GJ^{-1})[2]	N_2O emission (Gg N y^{-1})
Gas	1414	0.064 (0 - 0.700)	0.1 (0.0 - 1.0)
Oil	591	0.382 (0 - 1.782)	0.2 (0.0 - 1.1)
Coal; non-FBC	366	0.891 (0 - 6.364)	0.3 (0.0 - 2.3)
Coal; FBC	1.6	26.7 (4.4 - 49)	<0.1 (0.1 - 0.1)
Total			0.7 (0.0 - 4.5)

[1] Including feedstocks, excluding transport and bunkers, see Appendix 6-1; [2] Table 4-12.

Table 4-15. Method II: Dutch 1990 activity levels, emission factors and emissions of N_2O from mobile combustion

Mobile combustion	10^6 vehicle-km y^{-1} [1]	Emission factor ($g\ N_2O\ km^{-1}$)[16]	N_2O emission ($Gg\ N\ y^{-1}$)
Passenger cars			
- gasoline	50519	0.034 (0.021-0.106)[5]	1.1 (0.7-3.4)
- diesel	15293	0.031 (0.030-0.040)	0.3 (0.3-0.4)
- LPG	14233	0.034 (0.021-0.106)[6]	0.3 (0.2-1.0)
Freight			
- low duty gasoline	1698	0.045 (0.004-0.060)[7]	0.0 (0.0-0.1)
- low duty diesel	5551	0.031 (0.030-0.040)[8]	0.1 (0.1-0.1)
- low duty LPG	440	0.045 (0.004-0.060)[9]	0.0 (0.0-0.0)
- heavy duty trucks	3700	0.200 (0.029-0.840)[10]	0.5 (0.1-2.0)
- heavy duty trailers	2304	0.200 (0.029-0.840)[11]	0.3 (0.0-1.2)
Other			
- special vehicles gasoline[2]	48	0.045 (0.004-0.060)[12]	0.0 (0.0-0.0)
- special vehicles diesel[2]	307	0.200 (0.029-0.840)[13]	0.0 (0.0-0.2)
- buses	628	0.200 (0.029-0.840)[13]	0.1 (0.0-0.3)
- motorcycles	946	0.010 (0.001-0.013)[14]	0.0 (0.0-0.0)
- mopeds	1710	0.004 (0.000-0.005)[14]	0.0 (0.0-0.0)
Non road (water/rail)[3]	1517[4]	0.69 (0.10-2.90)[15]	0.7 (0.1-2.8)
Total			3.4 (1.5-11.5)

[1] Van Wee et al. (1993), see Appendix 6-2; [2] These are commercial vehicles not equipped for good transport; [3] Air not included; [4] In 10^6 kg fuel y^{-1}; [5] Assuming for 1990: 64.9% of vehicle kilometers was driven in cars without emission control; 7% with a new closed loop 3-way catalyst; 15.5% with an aged closed-loop 3-way catalyst; 12.7% with an open-loop catalyst (based on Baas, 1991); [6] As gasoline fuelled cars; [7] Assuming 100% km in cars without control; [8] As diesel passenger car; [9] As low duty gasoline; [10] 100% diesel; [11] As heavy duty trucks; [12] As low duty gasoline; [13] As heavy duty diesel; [14] As uncontrolled gasoline passenger cars; [15] g N_2O per kg fuel; based on heavy duty diesel truck; [16] From Baas (1991).

Table 4-16. Method II; Dutch 1990 activity levels, emission factors and emissions of N_2O from NOx deposition[1].

NOx deposition	NOx emission ($Gg\ N\ y^{-1}$)[2]	Emission factor (% of NOx-N)[3]	N_2O emission ($Gg\ N\ y^{-1}$)
Fossil fuel combustion	124	1 (0.2 - 1.25)%	1.2 (0.2 - 1.5)

[1] calculated as 1 (0.2 - 1.25)% of NOx-N *emissions*; [2] Apppendix 6-7; [3] Table 4-9

4.3.2.3 Industry

Total industrial emissions amoun to 11.6 (5.4 - 17.7) Gg N y^{-1}, and are all abiogenic. Method II uses the same emission factors as method I does for adipic acid and nitric acid production (Table 4-17). This method was also used for *National Environmental Outlook 3* (RIVM, 1993a). It is recognized that these emission factors are based on measurements outside the Netherlands.

Another industrial source, 1.1 Gg N_2O-N y^{-1}, has been identified in the Netherlands (VROM, 1993). The exact mechanism of N_2O formation is not clear, but may be industrial production of caprolactam (RIVM, 1993a). This illustrates the need for a structural inventory of industrial sources of N_2O.

Table 4-17. Method II: Dutch 1990 activity levels, emission factors and emissions of N_2O from industry; n.k. not known

Industry	Activity level (Gg N y^{-1})	Emission factor (g N_2O-N per kg product)	N_2O emission (Gg N y^{-1})
Nitric acid production	617[1]	17 (7-27) g N per kg N	10.5 (4.3 - 16.7)
Adipic acid production	0	191	0
Other chemical industry	n.k.	n.k.	1.1
Total			11.6 (5.4 - 17.7)

[1] Appendix 6-3; [2] See Table 4-12

4.3.2.4 Agriculture

Total agricultural emissions

Method II estimates total N_2O emissions from Dutch agriculture at 16.9 (4.7 - 28.8). Figure 4-1 shows that manure (35%) and synthetic fertilizers (26%) are major contributors. In addition, nitrogen leaching contributes by 11%. Most of the leached nitrogen comes from fertilizer or manure. Appendix 6-4 overviews the activity data used for Dutch agriculture.

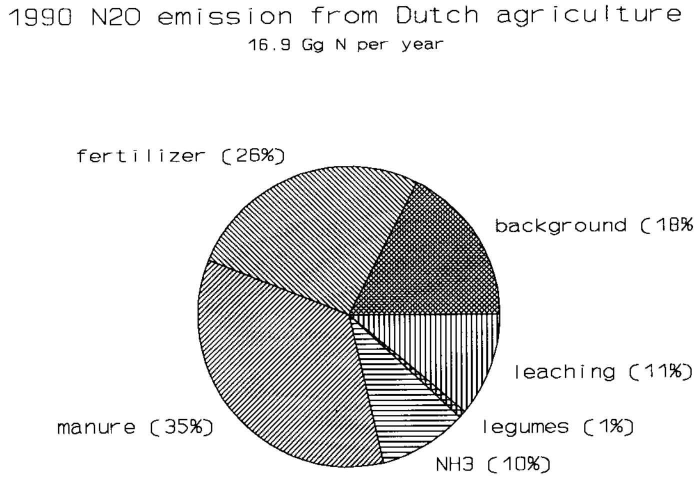


Fig. 4-1. 1990 emissions from Dutch agriculture using method II.

Anthropogenic background emissions

Background emissions are enhanced by 3.0 (0.6 - 11.1) Gg N y^{-1} (Tables 4-8 and 4-18). The most important reason is lowering of the groundwater table.

Synthetic nitrogen fertilizer

In the Netherlands 412 Gg synthetic N fertilizer is used, of which 8.6 Gg is emitted as NH_3 (Appendix 6-4). About 90% of the fertilizer is applied to mineral soils in the Netherlands. Total N_2O emissions are estimated to be 4.4 (1.2 - 5.5) Gg N y^{-1} in 1990 (Table 4-18).

Animal manure

Total N_2O emissions from animal manure are 5.8 (2.1 - 7.6) Gg N y^{-1}, of which 55% is emitted after use of manure as fertilizer. Emissions from stables/storage and meadows contribute 8 and 37%, respectively (Table 4-18).

Biological N_2 fixation

The nitrogen input by legumes is 15 Gg N y^{-1} (Table 4-18), of which 1 (0.2 - 1.25)% is emitted as N_2O. The resulting N_2O emissions are 0.2 (0.0 - 0.2) Gg N y^{-1}.

NH_3 emissions and NHx deposition

More than 90% of NH_3 emissions in the Netherlands are from agriculture (Van der Hoek, 1994). Agricultural NH_3 emissions are 164 Gg N y^{-1}, and the resulting biogenic N_2O emissions are 1 (0.2 - 1.25)%, or 1.6 (0.3 - 2.1) Gg N y^{-1}.

Leaching and run-off

Nitrogen leaching from agricultural soils is 183 Gg N y^{-1}. The resulting N_2O emissions from freshwater and coastal systems are 1.8 (0.4 - 2.3) Gg N y^{-1}.

N_2O formation in air containing NH_3

This source of N_2O should be attributed to both agriculture and energy, but the contributions of the two sectors are not distinguishable. Therefore this source is included in the category "other" (4.3.2.7).

Table 4-18. Method II: Dutch 1990 activity levels, emission factors and emissions of N_2O from agriculture

Agriculture	N flux (Gg N y^{-1})[1]	Emission factor (%)	N_2O emission (Gg N y^{-1})
Background (anthropogenic)			3.0 (0.6 - 11.1)[2]
Synthetic nitrogen fertilizer			
- mineral soils	363	1 (0.2 - 1.25)%	3.6 (0.7 - 4.5)
- organic soils	40	2 (1.25 - 2.5)%	0.8 (0.5 - 1.0)
Total	403[3]		4.4 (1.2 - 5.5)
Manure production in meadows			
- urine	82	2 (1.25 - 2.5)%	1.6 (1.0 - 2.0)
- faeces	54	1 (0.2 - 1.25)%	0.5 (0.1 - 0.7)
Total	136		2.2 (1.1 - 2.7)
Manure storage			
- deep-litter stable	0	5 (2.5 - 10)%	0
- anaerobic	366	0.1 (0 - 0.2)%	0.4 (0.0 - 0.7)
- acid treatment	0	5 (2.5 - 10)%	0
- veal calf manure treatment	5	2 (1.25 - 2.5)%	0.1 (0.1 - 0.1)
Total	371		0.5 (0.1 - 0.9)
Manure application			
- surface application: mineral soil	246	1 (0.2 - 1.25)%	2.5 (0.5 - 3.1)
- surface application: organic soil	37	2 (1.25 - 2.5)%	0.7 (0.5 - 0.9)
- injection	0	2 (1.25 - 2.5)%	0
Total	283		3.2 (1.0 - 4.0)
Emissions of NH_3			
- from manure	156	1 (0.2 - 1.25)%	1.6 (0.3 - 2.0)
- from synthetic fertilizer	9	1 (0.2 - 1.25)%	0.1 (0.0 - 0.1)
Total	164		1.6 (0.3 - 2.1)
Biological N_2 fixation	15	1 (0.2 - 1.25)%	0.2 (0.0 - 0.2)
Nitrogen leaching and run-off	183	1 (0.2 - 1.25)%	1.8 (0.4 - 2.3)
Total			16.9 (4.7 - 28.8)

[1] All N fluxes exclude NH_3-N, except biological treatment; see Appendix 6-4; [2] Table 4-8; [3] excluding greenhouse horticulture

4.3.2.5 Land use change

Important land use changes in the Netherlands took place in different periods. Land reclamation and deforestation started in the Middle Ages. Reforestation has been taking place since 1950. Changes in land cover such as drainage, poldering or forest extension influence background emissions of N_2O and are either included in the category agriculture as enhanced background emissions, or assumed to be negligible.

4.3.2.6 Waste

Method II yields N_2O emissions from waste of 0.3 (0.1 - 0.8) Gg N y^{-1} (Table 4-19). Most of these emissions are from sewage treatment plants.

Table 4-19. Method II: Dutch 1990 activity levels, emission factors and emissions of N_2O from waste (Gg N y^{-1}); n.q. not quantified

Waste	Activity level	Emission factor	N_2O emission
MSW incineration	3400 Gg y^{-1} [1]	12.7 (3.2 - 127.3) g N per ton[2]	<0.1 (0.0 - 0.4)
Sewage treatment	25.7 Gg N removed per year[1]	1 (0.2 - 1.25)% of N removed[3]	0.3 (0.1 - 0.3)
Landfills	? ton N dumped per year	1 (0.2 - 1.25)% of N dumped[3]	n.q.
Total			0.3 (0.1 - 0.8)

[1] Appendix 6-6; [2] Table 4-12; [3] Table 4-9

4.3.2.7 Other emissions

Total emissions

Total emissions in the category "other" are 1.6 (0.6 - 1.9) Gg N y^{-1}, with atmospheric deposition and nitrogen loading to surface waters as major contributors (Table 4-20).

Atmospheric formation

Due to anthropogenic emissions of NOx and NH_3 (from combustion processes and agriculture mainly), less than 0.1 Gg N_2O-N is formed in the troposphere (Table 4-20).

N loading of surface waters: sewage and industries

Using emission factor class 2 for nitrogen loading to surface waters, this source is estimated 0.6 (0.1 - 0.7) Gg N y^{-1}.

Non-agricultural NH_3 emissions; non-energy related NOx emissions

Ammonia emissions from industries and households cause enhanced biogenic N_2O emissions of 0.1 (0.0 - 0.2) Gg N y^{-1}. Other NOx emissions enhance biogenic N_2O emissions by 0.5 (0.1 - 0.6) Gg N y^{-1}.

Anaesthesia

In the Netherlands 0.335 Gg of N_2O is used for anaesthesia annually (Duyzer, pers.comm.).

Global warming

It is assumed here that the temperature in the Netherlands has not been effected yet by global warming.

Table 4-20. Method II: Dutch 1990 activity levels, emission factors and emissions of N_2O from the category "other"; n.q. not quantified

Other	Activity level[1]	Emission factor	N_2O emission (Gg N y^{-1})
Atmospheric formation (anthr.)	177 Gg NH_3-N emitted	0.009 (0 - 0.045)%[2]	<0.1 (0.0 - 0.1)
Other N-loading surface waters	N-loading (Gg N y^{-1})		
- industries, households	57	1 (0.2 - 1.25)%[3]	0.6 (0.1 - 0.7)
Other NH_3 and NOx emissions			
NH_3: industries, households	13	1 (0.2 - 1.25)%[3]	0.1 (0.0 - 0.2)
NOx: industries, other	51	1 (0.2 - 1.25)%[3]	0.5 (0.1 - 0.6)
Anaesthesia	0.3 Gg y^{-1}	n.q.	0.3 (0.3 - 0.3)[4]
Global warming	0 °C warming	n.q.	0
Total			1.6 (0.6 - 1.9)

[1] See Appendix 6-7; [2] See Table 4-12; [3] See Table 4-9; [4] range not known

4.3.3 Dutch 1990 emissions from all sources (method II)

Method II yields total Dutch N_2O emissions of 37.1 (13.0 - 69.7) Gg N y^{-1}, or 58.4 (20.5 - 109.5) Gg N_2O y^{-1} for the year 1990 (Table 4-21; Fig. 4-2). At least 95% of these emissions are anthropogenic, and almost two-thirds are biogenic. Agriculture is the most important sector, causing about half of the Dutch N_2O emissions.

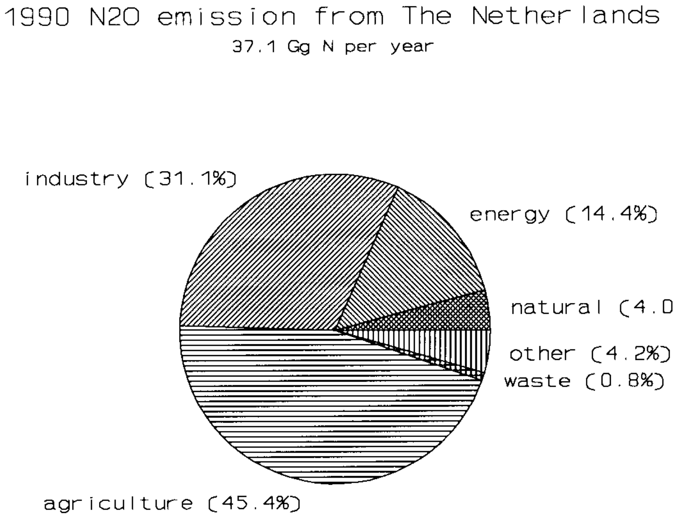


Fig. 4-2. Total N_2O emissions from the Netherlands in 1990 estimated with method II.

Table 4-21. Dutch emissions of N_2O in Gg N y^{-1} for 1990 calculated with method II; n.q. = not quantified

Source	N_2O emission (Gg N y^{-1})
Natural emissions	
- soils	1.5 (0.5 - 3.0)
- aquatic sources	n.q.
- atmospheric formation	<0.1 (0.0 - <0.1)
Total natural	1.5 (0.5 - 3.0)
Anthropogenic emissions	
Energy	
- stationary sources	0.7 (0.0 - 4.5)
- mobile sources	3.4 (1.5 - 11.5)
- NOx emissions	1.2 (0.2 - 1.5)
Industry	
- adipic acid	0.0 (0.0 - 0.0)
- nitric acid	10.5 (4.3 - 16.7)
- other	1.1 (1.1 - 1.1)
Agriculture	
- enhanced background emissions	3.0 (0.6 - 11.1)
- synthetic fertilizer	4.4 (1.2 - 5.5)
- manure in meadows	2.2 (1.1 - 2.7)
- manure in stables	0.5 (0.1 - 0.9)
- manure applied as fertilizer	3.2 (1.0 - 4.0)
- NH_3 emissions	1.6 (0.3 - 2.1)
- N_2 fixation	0.2 (0.0 - 0.2)
- leaching/run-off	1.8 (0.4 - 2.3)
Waste	
- waste incineration	<0.1 (0.0 - 0.4)
- sewage treatment	0.3 (0.1 - 0.3)
Other	
- atmospheric formation	<0.1 (0.0 - 0.1)
- non-agricultural N-load waters	0.6 (0.1 - 0.7)
- non-agricultural NH_3 emissions	0.1 (0.0 - 0.2)
- non-energy related NOx emissions	0.5 (0.1 - 0.6)
- anaesthesia	0.3 (0.3 - 0.3)
Total anthropogenic	35.6 (12.5 - 66.7)
Total emissions	
Total N_2O (Gg N y^{-1})	37.1 (13.0 - 69.7)
Total N_2O (Gg N_2O y^{-1})	58.4 (20.5 - 109.5)

4.4 Differences between method I and method II

Method I results in considerably lower emissions than method II (Table 4-22; Fig. 4-3). Using method I, Dutch anthropogenic N_2O emissions amount to 17.3 (6.3 - 38.0) Gg N y^{-1}, of which at least half are industrial (Table 4-6). Method II results in 37.1 (13.0 - 69.7) Gg N y^{-1} total emissions, of which more than 95% are anthropogenic, and more than half biogenic (Table 4-21). There are two reasons for these differences:

1. Method II identifies more sources of N_2O than method I.
   The following sources of N_2O are not included in method I: natural emissions, emissions induced by atmospheric deposition of NOx and non-agricultural NH_3, other chemical industries, background emissions from soils, emissions from stables, N leaching, sewage treatment, atmospheric formation, N input to surface waters, and use in anaesthesia. Nitrous oxide emissions from these sources are 11 Gg N y^{-1}. This explains about 55% of the difference in total emissions between the two methods (Table 4-22).

2. Emission factors are different.
   Emission factors used for soils are higher in method II than in method I. This may be correct, since in the Netherlands nitrogen is accumulating, which could result in higher percentage emissions. On the other hand, method I may underestimate fertilizer-induced emissions, since the IPCC emission factors are based on Eichner (1990), without correcting for emissions outside the sampling period. In chapter 3 it is argued why Eichner may be underestimating N_2O emissions for other reasons. The emission factors used in method II for road vehicles also differ from the IPCC method. The emission factors as given by Baas (1991) are used in method II, resulting in 3.4 Gg N y^{-1} from transport, which is somewhat lower than the 3.7 Gg of method I. Likewise, N_2O emissions from waste incineration are lower in method II. Different emission factors explain about 45% (9 Gg N y^{-1}) of the difference between method I and II (Table 4-22).

Figure 4-3 shows that there is little overlap in the uncertainty ranges of the two methodologies. This clearly illustrates the uncertainties that still exist about emissions of N_2O. Nevertheless, knowledge about a number of nitrous oxide emissions has increased. There is little doubt that additions of nitrogen to soils or surface waters in whatever form, result in emissions of N_2O. Similarly, it is clear that combustion processes are a source of N_2O, and that catalysts in cars tend to increase emissions from mobile combustion. Despite the large spatial and temporal variability of the fluxes, it is possible to define emission factors. More research will clearly improve our knowledge and consequently the methodologies, but will not readily lead to more certain estimates.

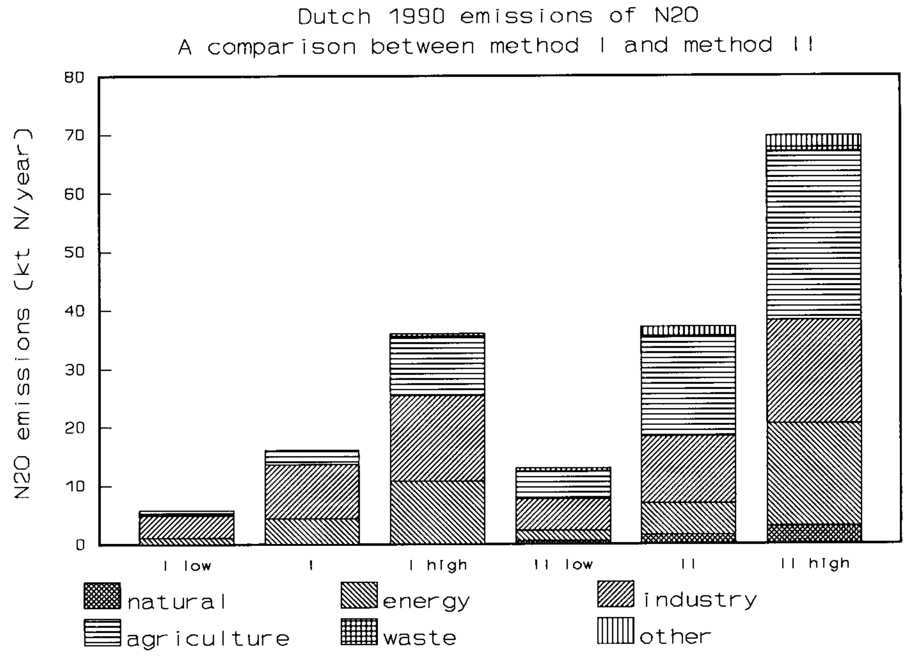


Fig. 4-3. Dutch 1990 emissions according to method I (IPCC methodology) and method II (update of *National Environmental Outlook 3*).

Table 4-22. Dutch 1990 emissions of N_2O (in Gg N y^{-1}): a comparison between method I and method II; n.q. not quantified

Source	Method I	Method II	Difference II - I	Remarks
Natural emissions				
- soils	n.q.	1.5	1.5	not included in method I
- aquatic sources	n.q.	n.q.	n.q.	not included in methods I and II
- atmospheric formation	n.q.	<0.1	<0.1	not included in method I
Total	n.q.	1.5	1.5	
Anthropogenic emissions				
Energy				
- stationary sources	0.6	0.7	<0.1	methods use different emission factors
- mobile sources	3.7	3.4	-0.3	methods use different emission factors
- NOx emissions	n.q.	1.2	1.2	not included in method I
Industry				
- adipic acid	0.0	0.0	0.0	method I = method II
- nitric acid	10.5	10.5	0.0	method I = method II
- other chemical industry	n.q.	1.1	1.1	not included in method I
Agriculture				
- enhanced background emissions	n.q.	3.0	3.0	not included in method I
- fertilizer	1.1	4.4	3.4	methods use different emission factors
- manure in stables	n.q.	0.5	0.5	not included in method I
- manure applied as fertilizer[1]	1.3	5.4	4.1	methods use different emission factors
- NH_3 emissions	n.q.	1.6	1.6	methods use different emission factors
- N_2 fixation	<0.1	0.2	0.1	methods use different emission factors
- leaching/run-off	n.q.	1.8	1.8	not included in method I
Waste				
- waste incineration	<0.1	<0.1	-0.0	methods use different emission factors
- sewage treatment	n.q.	0.3	0.3	not included in method I
Other				
- atmospheric formation	n.q.	<0.1	<0.1	not included in method I
- non-agricultural N-load waters	n.q.	0.6	0.6	not included in method I
- non-agricultural NH_3 emissions	n.q.	0.1	0.1	not included in method I
- non-energy NOx emissions	n.q.	0.5	0.5	not included in method I
- anaesthesia	n.q.	0.3	0.3	not included in method I
- global warming	n.q.	0.0	0.0	not included in method I
Total	17.3	35.6	18.3	
Natural + anthropogenic	17.3	37.1	19.8[2]	

[1] This includes manure produced in meadows; [2] 11 Gg because sources are not included in method I and 9 Gg because of different emission factor used

4.5 Conclusions

Two methods are described to estimate N_2O emissions from the Netherlands. Method I is the methodology as proposed during an IPCC workshop (Van Amstel, 1993). This methodology was proposed as a default method for reporting greenhouse gas emissions. Method II is an update of the methodology used in the RIVM *National Environmental Outlook 3* (RIVM, 1993a,b).

There are considerable differences between the two methods. Dutch emissions amount to 17.3 (6.3 - 38.0) Gg N y^{-1} using method I and 37.1 (13.0 - 69.7) Gg N y^{-1} for method II. The difference has two major causes: (i) method II includes more sources than method I, and (ii) the two methods use different emission factors.

In chapters 5 and 6 method II is used to present past and future emissions of N_2O from the Netherlands. There are several reasons why method II is to be perferred over method I. Most importantly, method II is more complete. It includes almost all known sources of N_2O, while method I is restricted to the most important sources on the global scale. Secondly, method II has been evaluated, where possible, against Dutch research. Thus, the emission factors used in method II seem more appropriate than the globally averaged factors proposed in method I. Finally, applying method I to global activity data indicates that method I indeed underestimates present N_2O emissions; method I results in global emissions of about 0.5 - 4 Tg N y^{-1}, while the increase in atmospheric N_2O indicates that anthropogenic emissions must be between 3.9 and 5.1 Tg N y^{-1} (see chapter 3.2.3).

Dutch N_2O emissions are for more than 95% anthropogenic at present according to method II (Fig. 4-2). About half of the Dutch emissions stem from agricultural activities. The use of fertilizers (both synthetic and manure) is an important source of N_2O. Fertilizers increase N_2O emissions from agricultural soils by 7.6 Gg N y^{-1} (4.4 + 3.2 Gg N y^{-1}; Table 4-21). In addition, a considerable amount of the fertilizer leaches from the soil, and causes N_2O emissions from, for instance, surface waters (1.8 Gg N y^{-1}). Animal manure is an important source of NH_3, which, after atmospheric deposition, increases soil emissions of N_2O (1.6 Gg N y^{-1}). And production of nitric acid, mainly used as feedstock for synthetic fertilizers, is an important industrial source of N_2O in the Netherlands (10.5 Gg N y^{-1}). Another important single source of N_2O in the Netherlands is transport (3.4 Gg N y^{-1}). In particular, passenger vehicles with three-way catalytic converters appear to be an important source of N_2O, which also may increase in the near future due to aging of the catalysts.

5 REDUCTION OF ANTHROPOGENIC N_2O EMISSION

5.1 Introduction

This chapter describes options to reduce anthropogenic emissions of N_2O and quantifies their potential effects. Both technical and volume-type options are described. In method II most emissions of N_2O are calculated as "activity" x "EF", where "activity" is the activity level, and "EF" an emission factor. Emissions can be reduced by (i) decreasing the emissions per activity, or (ii) decreasing the activity level. Most technical options decrease emission factors or improve efficiency, while volume-type options typically directly reduce the activity level.

The aim of this chapter is to give a general overview of options to reduce N_2O emissions and to select specific options for Dutch emissions to be used in the *additional policy* projections in chapter 6. At present there is no specific N_2O policy in the Netherlands. Current policy, in particular abatement of acidification, eutrophication, smog and global warming by other greenhouse gases can indirectly increase or decrease the amount of N_2O formed.

This document adopts the definitions of market status categories from the International Energy Agency (Table 5-1). As far as possible, the technical potential of options to reduce Dutch N_2O emissions is quantified. This is the reduction that can be expected once a technology is fully implemented. It is assumed that all deployed and demonstrated technologies can be implemented by 2000. If technologies are prospective or conceivable, their potential effect for the year 2000 is estimated. The economic potential of options is not investigated in this study.

Table 5-1. Definition of categories of market status according to the International Energy Agency[1]

IEA categories	IEA definition	General description
Conceivable technologies:	Those which still require further basic research or laboratory development before the technical feasibility can be determined, and where therefore only very approximate and possibly unreliable estimates of cost and performance exist.	Those technologies which are at the design concept/research stage.
Prospective technologies:	Those which have been shown to be feasible and applicable at the laboratory or pilot scale, for these technologies it is fairly certain that their adoption on a commercial scale is technically possible, but the scale factors and timing involved in building and operating a commercial-scale plant may not be fully understood, so that estimates of cost and performance are uncertain and tentative.	This encompasses those technologies that fall in the region spanning the later stages of research through to small-scale pilot plants or an equivalent stage.
Demonstrated technologies:	Those that have already been tested on a commercial or near-commercial scale in some country, but which are not yet deployed commercially. Their current cost and performance estimates are likely to be fairly close to eventual net return.	This covers the region from small-scale pilot plant through to large pilot plant/specification of the detailed engineering concept/detailed design stage.
Deployed technologies:	Those that are used commercially, and of which cost and performance in commercial operation are already well-defined.	This encompasses all technologies that are currently available as off-the-shelf products, or are close to this stage.

[1] source: UK Dept. Trade and Industry, 1994

5.2 Reduction of N_2O emissions from energy use

Several options to reduce emissions of N_2O from combustion are listed in Table 5-2. Options are defined for N_2O emissions from (a) stationary combustion, (b) mobile combustion and (c) soils and surface waters due to atmospheric deposition of NOx.

Existing policy
Currently there no countries in which action is taken to reduce N_2O emissions from stationary and mobile combustion. However, N_2O emissions may be affected indirectly by other environmental policy. Abatement of acidification, smog and global warming by CO_2 and CH_4 may influence energy-related N_2O emissions. For instance, energy saving, increased energy efficiency, and a switch to non-fossil types of energy decrease emissions of acidifying compounds, smog precursors, and greenhouse gases (CO_2, CH_4, N_2O) simultaneously. A decrease in deposition of NOx on soils and surface waters also decreases the biogenic soil emissions of N_2O. On the other hand, technologies to reduce NOx emissions may increase the production of N_2O during fossil fuel combustion. This is especially obvious in mobile combustion, where the net effect of NOx abatement by 3-way catalysts is clearly an increase in N_2O: N_2O emissions from gasoline vehicles with old 3-way catalyst converters exceed those from uncontrolled vehicles by a factor of 4 to 16 (De Soete, 1993).

Techniques to reduce N_2O in flue gases
There are three ways to avoid or reduce emissions of N_2O in flue gases (Olivier, 1993b; Reimer et al., 1992, 1994; De Soete, 1993).
- *(i) Avoiding N_2O emissions by shifting the combustion temperature.* Creation of N_2O in the gasphase can be avoided by shifting the combustion temperature to below 800 °C or beyond 950 °C. Production of N_2O increases with temperature, but at temperatures higher than 950 °C, thermal destruction of N_2O occurs. As a result, emissions are highest at temperatures in the range 800 - 950 °C. A shift outside this range may effectively reduce N_2O emissions. However, in some cases it could lead to enhanced emissions of other compounds, such as NOx.
- *(ii) Gas phase destruction of N_2O (afterburning).* Gas phase destruction of N_2O is possible by incineration at temperatures higher than 950 °C. At these temperatures a relatively large amount of H and OH radicales are produced, enhancing the destruction of N_2O (Reimer et al., 1994):

$N_2O \text{ -> } N_2 + 1/2\ O_2$
$N_2O \text{ -> } NO + 1/2\ N_2$

Gas phase destruction is recommendable when N_2O concentrations are relatively high (> 1000 ppmv), and reductions of >90% can be achieved within a few seconds; a catalytic reduction step may reduce the remaining 10% (Bouscaren et al., 1993). Concentrations of N_2O from 10% and higher, which is not unusual in industrial production of adipic acid, can be reduced by over 99% by using N_2O as an oxidizer instead of oxygen, for instance, in the combustion of hydrocarbons or H_2 with N_2O as oxidizer (De Soete, 1993). The NO

formed may be recyclable (Reimer et al., 1994).
- *(iii) Catalytic destruction of N_2O.* Direct catalytic reduction of N_2O to N_2 and O_2 is an option that can be applied to flue gases with concentrations of N_2O below 200 ppmv (De Soete, 1993). Catalysts that reduce N_2O are many precious metals, transition and earth-alkaline metals and their oxides (for instance, CuO, CaO, MNO_2, V_2O_2, CeO_2, V_3O_2). Reductions of the N_2O concentrations up to 80% have been reported (Bouscaren et al., 1993). Adipic acid producers aim at 98% reduction of the N_2O formed by a catalyst in development (Reimer et al., 1994). A catalyst is not yet commercially available.

Reduction options in stationary combustion (options a.1 - a.10)

- *Conventional power plants (a.1).* The N_2O concentrations in flue gases of conventional power plants are usually well below 10 ppmv (De Soete, 1993). These N_2O concentrations are too low for catalytic reduction of N_2O. The overall combustion temperature is usually well beyond 950 °C, as a result of which most N_2O is destroyed before emission. The N_2O emitted could be the result of local drops of the temperature below 900 °C. Avoiding local temperature decreases may therefore be the most effective way to reduce N_2O emissions, in particular in older power plants (option a.1). Theoretically, it must be possible to avoid a major part of the N_2O emissions this way. It is estimated here that N_2O emissions can thus be reduced by at least 10%. This could be achieved, for instance, by improved technical specification in order to limit the events that temperatures drop (prospective technology, needing further research), or development of higher performance combustors (conceivable technology).
- *NOx abatement by SCR or SNCR (a.2).* The effects of NOx reduction techniques in stationary combustion on N_2O emissions are not exactly known. Selective Catalytic Reduction of NO (SCR) may increase N_2O emissions, but this has only been observed in the laboratory scale. Selective Non Catalytic reduction (SNCR) may result in higher emissions than SCR (Oonk, pers.comm., see chapter 3.3.2). A shift of the temperature in SNCR may reduce N_2O production, but simultaneously increase NOx emissions. More N_2O is formed when using urea or cyanuric acid than when using NH_3. Thus, when chosing SCR or SNCR (with regard to N_2O formation): chose SCR in preference to SNCR. When using SNCR: chose NH_3 in preference to ureum or cyanuric acid. Currently these techniques are not common in stationary combustion in the Netherlands, but SCR is obligatory in new coal-fired power plants, while SNCR is a technique that may be applied in waste incineration. These are all deployed technologies.
- *Fluidized Bed Combustion (FBC) (a.3 - a.6).* Fluidized bed combustors emit relatively high amounts of N_2O, because of the low combustion temperature (800 - 900 °C). Afterburning of N_2O, shortly increasing temperatures above 950 °C, could reduce the N_2O concentrations by an estimated 90% (a.3) (Oonk, pers.comm.). This is demonstrated technology. Fluidized bed combustion results in N_2O concentrations in flue gases of 30 - 150 ppmv (De Soete, 1993). These concentrations are suitable for catalytic reduction of N_2O (a.4). Catalysts for N_2O are in development, and can presumably be implemented within a decade. Catalysts typically reduce N_2O concentrations by over 80%. Another option is addition of limestone (CaO), which reduces N_2O and SO_2 concentrations simultaneously (a.5). Finally, replacing FBC by conventional coal combustion, or

gasification of coal, is an effective way to avoid emissions of N_2O (a.4) (Blok and De Jager, 1994). After gasification combustion temperatures are higher than 950 °C.
- *Fuel switch and energy saving (a.7 - a.10).* Since technical options to reduce N_2O production in conventional power plants are not readily available, the most effective way to reduce energy-related emissions may be reducing the amount of fossil fuels used. These options involve deployed technologies. A shift from coal to oil to gas for electricity generation would also reduce N_2O emissions. Emissions from gas- and oil-fired plants are about 90 and 60% lower than coal-fired conventional power plants (Table 4-12). Renewable sources of energy such as wind and solar energy do not produce N_2O at all. Apart from zero N_2O production, renewables also show low emissions of NOx, CO_2 and CH_4. Biomass and waste digestion or gasification may be potential, but probably low source of N_2O. Although scarcely investigated, their emissions are expected to be close to or lower than to those of natural gas. Indeed, emissions from wood-fired fluidized bed combustors were found to be two orders of magnitude lower than those from a coal-fired combustors (Lecker, 1993). Hence, it is assumed here that a shift from coal to renewables may decrease emissions per GJ by at least 90%.

In general, an increase in energy efficiency will reduce N_2O emissions, because in general the less fossil fuels are used, the less N_2O will be produced.

Techniques for N_2O reduction in mobile combustion (options b.1 - b.8)
In transport, N_2O is mainly formed during NOx abatement by engines equipped with 3-way catalytic converters. The N_2O production increases with the age of the catalytic converter. Since catalytic converters have been introduced relatively recently in the Netherlands, the average N_2O emission factor for Dutch road vehicles is likely to increase during the coming decades along with catalyst aging and increasing penetration of 3-way catalytic converters. The following reduction techniques are known:
- *Temperature control (b.1).* Controlling the temperature may avoid some formation of N_2O (option b.1), but the effect is not known, and hardly investigated. It is also not clear how N_2O reduction by temperature control affects emissions of other gases, such as NOx and CO.
- *No old 3-way catalytic converters (b.2).* N_2O emissions per vehicle-kilometer for cars without 3-way catalytic converters can be up to 80% lower than for cars having old catalysts, based on emission factors used in method II (Table 4-12). Thus, if 3-way catalytic converters were removed from the Dutch car market, N_2O emissions would be reduced considerably (option b.2). However, this option causes a considerable increase in emissions of acidifying compounds and smog precursors, so is considered not preferable. The N_2O emissions from traffic can also be reduced by avoidance of aging of catalysts: cars with new 3-way catalytic converters emit on average 70% less N_2O than cars with old 3-way catalytic converters. In order to reduce N_2O emissions effectively, catalytic converters would have to be replaced before N_2O production increases. For the senario calculations (chapter 6) it is tentatively assumed that all catalysts are "old" after about two years, however, actual aging may proceed much faster. The feasibility of this option therefore depends on the required frequency in catalyst replacement, which could be determined by regular monitoring of N_2O production in vehicles.
- *Development of a new catalyst (b.3).* Technically it may be possible to develop a catalyst

for cars with low emissions of N_2O as well as NOx, VOC, and CO. However, it is not at all likely that such a catalyst will become available before 2000.

- *Development of low NOx engines (b.4).* A major part of N_2O from traffic is formed during catalytic reduction of NOx to N_2. Therefore oxidation catalysts, that do not reduce NOx emissions, do not show enhanced N_2O emissions. Development of engines that do not require a catalytic reduction of NOx in exhaust gas is therefore a promising option to reducing N_2O emissions. Low NOx engines are considered a prospective option here. The same is valid for the use of fuel cells for car propulsion, reducing all types of emissions. Especially the application of solid polymer fuel cells can be considered a promising option.
- *Fuel switch and energy saving (b.5 - b.7).* It is clear that emissions of N_2O from mobile combustion are not easily reduced by technical means. Therefore, as for stationary combustion, an overall reduction in N_2O producing activities is probably be most effective way to reduce emissions in the short term. These include a reduction in kilometers driven in road-vehicles, especially those with 3-way catalystic converters (option b.5). Use of renewable sources of energy (electric vehicles using solar energy for instance) reduces N_2O emissions (option b.6). Also a shift to trains or other electric vehicles fueled by power plants would be an improvement. Gas- and coal-fired power plants emit on average 0.1 and 0.9 g N_2O-N per GJ, respectively, while emissions from passenger vehicles may range from 0.6 g N_2O-N per GJ for uncontrolled gasoline cars to 0.9 - 1.9 g N_2O-N per GJ for diesel cars to 11 - 76 g N per GJ for gasoline vehicles having an old 3-way catalytic converter (Olivier, 1993b). Similar conclusions can be drawn for transport of freight (Olivier, 1993b). Emissions from biofuelled vehicles are not known. However, it seems likely that biofuels used in diesel-type of engines without 3-way catalysts emit less N_2O than the present 3-way catalytic converter-equipped vehicles. Increase of energy efficiency (option b.7) reduces fuel use, which can result in a decrease in N_2O production.
- *Driving behavior (option b.8).* The amount of N_2O emitted by vehicles depends on many factors. One of them is driving behavior. Emissions are found to be high during starting, especially during a cold start, when the catalyst teperature is low (Jobson et al., 1994). At an average speed between 20 and 40 km h^{-1}, cars were observed to emit twice as much N_2O per km at a speed between 60 and 120 km h^{-1} (Bailey and Williams, 1990). Testing procedures simulating urban driving or traffic jams show in general higher emissions than testing procedures simulating highway driving. In addition, emissions seem to increase with vehicle size. Differences in car size and driving behavior are important reasons why emission factors for the USA cannot be used for Europe, or other parts of the world. Dutch emissions of N_2O could be reduced by decreasing urban driving and the amount of traffic jams (option b.9).

Options to reduce emissions due to atmospheric deposition of NOx (options c.1 - c.2)

It is not possible to directly influence biogenic N_2O production in soils caused by NOx deposition. These N_2O emissions can only be avoided by a reduction in NOx emissions. The Dutch policy goal to reduce acidification is to reduce NOx emissions by 80 - 90% relative to 1980 by the year 2010. Implementation of the formulated measures will reduce emissions by 55 - 60% (RIVM, 1993a,b). N_2O emissions due to NOx deposition can be expected to decline simultaneously. However, catalysts used for NOx reduction could increase in N_2O emissions as outlined above.

Conclusion

For stationary combustion, a number of options to reduce N_2O emissions are formulated. For instance emissions from electricity generations may be reduced by at least 10% by improvement of the combustion process in relatively old power plants. And emissions of N_2O from fluidized bed combustors can be reduced by at least 80% by afterburning. These two options have the potential to reduce 1990 emissions from stationary combustion in the Netherlands by 15% (see Table 5-7).

In mobile combustion no feasible technologies for N_2O reduction are currently available that do not simultaneously increasing emissions of acidifying compounds and smog precursors. It is not likely that new technologies will become available before the end of the century. It may also be impossible to reduce biogenic emissions induced by atmospheric NOx deposition, because the effect of NOx abatement on N_2O formation during the burning process is not clear.

Several technical options are promising, but need considerable further investigation or development. These include early replacement of 3-way catalysts in vehicles, development of modified combustors, low-N_2O 3-way catalysts in cars, low-N_2O NOx reduction in stationary combustion, low-NOx engines and electric vehicles.

In conclusion, it is clear that few end-of-pipe technologies to reduce emissions of N_2O are available at present. However, there are other options that reduce N_2O producing activities effectively. These include a shift from coal to oil to gas to renewable sources of energy. In general, energy saving, improved energy efficiency and a reduction in automobility automatically lead to a reduction in N_2O emissions as a result of a reduction of fossil fuel use.

Table 5-2. Overview of options to reduce emissions of N_2O from stationary combustion, quantifying the technical potential to reduce N_2O emissions (in % of the present emission per activity) for several options; n.q. = not quantified

Option	for reduction of N_2O emission from energy use	Potential reduction[1]	Market status category of the technology[2] / Remarks
a	<u>Stationary combustion</u>		
	Conventional power plants		
a.1	Avoidance of local temperature lower than 900 °C by improvement of combustion process (geometry), development of modified/optimized combustors	>10%	prospective/conceivable
a.2	NOx reduced by SCR or SNCR: SCR is preferred to SNCR, and in SNCR using NH_3 is preferred to ureum/cyanuric acid	n.q.	deployed
	Fluidized bed combustion		
a.3	Afterburning of N_2O	90%	demonstrated
a.4	Catalytic reduction	>80%	prospective
a.5	Limestone addition	n.q.	prospective
a.6	Use no FBC (but conventional combustion or gasification)	>90%	demonstrated
	Fuel switch and energy saving		
a.7	Switch from coal to oil to gas	<90%	deployed
a.8	Switch to non-fossil sources of energy	>90%	deployed
a.9	Increase in energy efficieny	n.q.	deployed
a.10	Other energy saving	n.q.	deployed
b.	<u>Mobile combustion</u>		
	Technical options		
b.1	Controlling temperature conditions of 3-way catalyst	n.q.	conceivable
b.2	Using no (old) 3-way catalysts for cars/trucks	>70%	deployed[3]
b.3	Development of new catalysts which also limit emissions of N_2O	n.q.	conceivable
b.4	Development of low NOx engines for cars	n.q.	prospective
	Fuel switch, energy saving and other		
b.5	Reducing automobility	n.q.	deployed
b.6	Switch to non-fossil sources of energy	>90%	deployed
b.7	Increase in energy efficieny	n.q.	deployed
b.8	Decrease in urban driving and traffic jams	n.q.	deployed
c	<u>Emissions due to atmospheric deposition of NOx</u>		
c.1	Technical reduction of NOx emissions	n.q.	deployed[4]
c.2	Fuel switch and energy saving (see a.9 - a.12 and b.6 - b.9)	n.q.	deployed

[1] Theoretical technical potential to reduce 1990 emission (%); [2] Category refers to technology involved; see Table 5-1; [3] No use of 3-way catalysts will result in extra emissions of NOx, CO, and VOC and is therefore not considered a preferable option here; early replacement of catalysts, so that only new catalysts are used, is only feasible if aging proceeds slowly enough; [4] Possibly extra N_2O formation, therefore not a preferable option

5.3 Reduction of N_2O emissions from industry

Options to reduce emissions of N_2O from (d) adipic acid production, (e) nitric acid production and (f) other industries are listed in Table 5-3. These options mainly include technical options, reducing the amount of N_2O emitted during production processes. This overview is based mainly on available literature.

Existing policy
The N_2O formed during adipic acid production can be relatively easily reduced by combustion (Table 5-3). This technology is being implemented voluntarily at present by adipic acid producers worldwide to reduce N_2O emissions (DuPont, 1991). Adipic acid is not produced in the Netherlands, but the techniques used in adipic acid production may be interesting for other industrial N_2O emissions. In addition, policies reducing the amount of mineral fertilizer used may indirectly influence nitric acid production.

Adipic acid production (options d.1 - d.5)
- *Thermal dissociation at 1200 - 1500 °C (option d.1).* The concentrations of N_2O in flue gases of adipic acid plants are suitable for combustion (see 5.3). Incineration of N_2O is technically and economically feasible (Reimer et al., 1992, 1994). Globally, about 32% of the N_2O formed during adipic acid production is currently destroyed accidentally by incineration during NOx abatement (Olivier, 1993). Incineration of N_2O could yield reduction rates of at least 98% (De Soete, 1993).
- *Catalytic dissociation (option d.2).* A catalyst for N_2O reduction from adipic acid production is being developed at present and may become available within a few years (Reimer et al., 1994). Industries aim at 98% reduction of N_2O.
- *Conversion to recoverable NO (option d.3).* Destruction of N_2O to recyclable NO by thermal conversion has been demonstrated in a pilot-scale reactor, in which over 99.8% of the N_2O was destroyed (Reimer et al., 1992).
- *Alternatives (options d.4 and d.5).* Options d.4 and d.5 concern alternative processes or products, and are longer term options requiring further investigation.

Nitric acid production (options e.1 - e.4)
- *Catalytic reduction (option e.1).* Concentrations of N_2O in flue gases of nitric acid plants may range from 300 to 1700 ppmv (De Soete, 1993), which are more suitable for catalytic reduction than for themal dissociation (see 5.3). Catalytic reduction to N_2 and O_2 could theoretically reduce 80% of the N_2O in flue gases (Bouscaren et al., 1993). A similar catalyst as in fluidized bed combustion (FBC) and adipic acid production can be used. These catalysts perform at relatively high temperatures (400 - 600 °C), which is not a problem in FBC and adipic acid production, where prevailing tempertures are sufficiently high. In nitric acid production a disadvantage of catalytic N_2O reduction may be the extra energy required to reach 400 - 600 °C, which is needed for catalytic reduction (Oonk, pers.comm). It is therefore desirable to develop a catalyst performing at lower temperatures, unless heat from for instance other nearby industries could be used for this purpose. A catalyst for nitric acid production can be technically available before 2000. Implementation may take time, and by 2000 may well be an optimistic assumption, but

not impossible.
- *Optimizing the production process (option e.2).* Optimizing the production process is another option to reduce N_2O emissions, but this also requires further research. Monitoring of N_2O production in different nitric acid producing plants is required to indicate processes of lower and higher emissions.
- *Total effect of e.1 and e.2.* It is assumed here that options e.1 and e.2 can reduce emissions of N_2O by at least 80% within the coming decade.
- *Alternatives (options e.3 and e.4).* Reduction of the production volume by alternative processes or alternatives for application of nitric acid, for instance, by decreasing N fertilizer use in agriculture, may also reduce N_2O emissions during industrial production.

Other industrial emissions

In the Netherlands N_2O emissions have been observed in other chemical industries (Olivier, 1993a, VROM, 1993). It is not clear whether these are process emissions, or a result of catalytic NOx reduction. Before suggesting an option to reduce these emissions, we need to know the process of N_2O formation. There are most probably still unidentified industrial processes leading to N_2O emissions (Olivier, 1993b; Oonk, pers.comm.; chapter 3.2.2). Some of the options mentioned above may be applicable to these processes.

Conclusion

Emissions from adipic acid production can be avoided by currently available technologies, but adipic acid is not produced in the Netherlands. Emissions from nitric acid production can theoretically be reduced by catalytic reduction. A similar catalyst as in adipic acid production may be used, however, to avoid extra energy input a catalyst preforming at relatively low temperatures need to be developed. A catalytic reduction step, possibly in combination with process adaptation, is therefore considered a conceivable technology, technically available, and possibly implementable by 2000. It could reduce N_2O emissions in nitric acid by 80%, and Dutch industrial 1990 emissions by about 70% (see also Table 5-7).

Table 5-3. Overview of options for reduction of N_2O emissions from industrial processes, quantifying the technical potential to reduce N_2O emissions (in % of the present emission per activity) for several options

Option for reduction of N_2O emission from industries		Potential reduction[1]	Market status category of the technology[2] / Remarks
d	*Reduction of N_2O formed during adipic acid production*		
d.1	Thermal dissociation	>98%	deployed
d.2	Catalytic dissociation to N_2 and O_2	>98%	demonstrated
d.3	Conversion to recoverable NO	>99%	prospective
d.4	Alternative production process	n.q.	conceivable; long-term
d.5	Alternatives for application of nylon	n.q.	conceivable; long-term
e	*Reduction of N_2O formed during nitric acid production*		
e.1	Catalytic reduction to N_2 and O_2		conceivable; before 2000[3]
e.2	Modifying/optimizing production process		conceivable; before 2000
	e.1 + e.2	>80%	
e.3	Alternative production process	n.q.	conceivable; long-term
e.4	Alternative for application of nitric acid	n.q.	conceivable; long-term
f	*Reduction of N_2O from other industries*		
	-		

[1] Theoretical technical potential to reduce 1990 emissions (%); n.q. = not quantified; [2] Category refers to technology involved; see Table 5-1; [2] May require extra energy

5.4 Reduction of N_2O emissions from agriculture

Available options to reduce N_2O emissions from (g) enhanced background emissions, (h) fertilizers, (i) storage of animal manure, (j) atmospheric deposition of NH_3, (k) biological N_2 fixation and (l) nitrogen leaching are listed in Table 5-4. At present, there is no specific policy in the Netherlands or other countries to reduce N_2O, although agricultural N_2O emissions are affected by policy measures to mitigate acidification, dessication, eutrophication, and pollution of groundwater. Synthetic fertilizer and manure are major sources of N_2O in a Western European country like the Netherlands. As for the other sources the emissions of N_2O can be abated by reducing of the emission factor and the volume of nitrogen production and use. In the following, several options to reduce N_2O emissions are described and evaluated for the Dutch situation. Nevertheless, the conclusions probably apply to all countries in Western Europe and North America.

Options to reduce background emissions (g.1, g.2)
Background emissions from soils may be enhanced as a result of lowering the groundwater table. This may hold for organic soils in particular (Table 4-8). In the Netherlands, lowering of the groundwater table is done for agricultural purposes, but leads to dessication in natural terrain, which has several adverse effects on ecosystems. Therefore, the Dutch government aims at reducing the area of dessicated natural terrain by 25% by the year 2000 relative to 1985. This goal will be hard to achieve (RIVM, 1993a,b). Approximately 10% of the Dutch land area is natural terrain (including forests). If the 25% is to be realized, enhanced background emissions of N_2O will be reduced in 2.5% of the Dutch land area, leading to a probably small reduction in N_2O emissions because natural terrains are usually found on mineral soils (option g.1). To be effective for N_2O, the dessication in natural as well as agricultural terrain needs to be halted (option g.2). The total effect of options g.1 and g.2 is tentatively estimated to be 10%.

Options to reduce emissions from fertilizer use (options h.1 - h.12)
The use of organic and synthetic N fertilizers is a source of N_2O. Only part of the fertilizer is taken up by crops as a result of management practices and environmental conditions. The remainder is lost to the atmosphere as NH_3, NO, NO_2, N_2O, or N_2, or leached as NO_3^- or NH_4^+. Fertilizer nitrogen may also accumulate as soil organic matter. Most of the nitrogen applied is, over the years, denitrified in the soil, or in groundwaters, surface waters, sewage treatment plants, or in natural soils after atmospheric deposition of NH_4^+. In addition, NH_3 emissions may lead to N_2O formation in the polluted atmosphere.

Three types of options to reduce fertilizer-induced N_2O emissions are formulated here: (h.1 and h.2) a shift towards lower emission factors, (h.3 - h.9) a more efficient use of fertilizers, and (h.10 - h.12) some other options.

- *(h.1, h.2) A shift towards class 1 emissions.* A shift towards lower emission factors (Table 4-9) causes lower N_2O emission per kg of fertilizer. This can be achieved by (h.1) surface application of organic fertilizers rather than fertilizer injection, and (h.2) by a reduction of the area of organic soils used in agriculture. Neither option has priority in the Netherlands. Animal manure is only allowed as fertilizer when it is injected into the soil in the Netherlands in order to avoid NH_3 emissions. And a switch from organic to mineral soils may be difficult to realize. In conclusion, a shift towards "class 1" emissions is hardly possible in the Netherlands.

- *(h.3 - h.9) Improved fertilizer efficiency.* An improvement in fertizer efficiency, leading to a reduction in N-input into agricultural soils, may be an effective way to reduce N_2O emissions. In 1990 412 Gg of synthetic fertilizer, and 359 Gg of manure N was applied to Dutch soils (Appendix 6-4). Fertilizer consumption can be reduced considerably with no or relatively small losses of yield in the Netherlands (Worrell, 1994). Indeed, present Dutch policy ("derde fase mestbeleid") results in a 55% and 53% reduction of synthetic and organic fertilizer use by 2010, respectively (Van der Hoek, 1994, Appendix 6-4). An additional 10% reduction seems feasible, at least for synthetic fertilizers and probably for manure N as well. Thus it is assumed that a further reduction to 65% is feasible. Table 5-4 lists several options to achieve this.

Options h.3 - h.7, improving fertilizer efficiency, are deployed technologies and several are included in current Dutch policies. They can be implemented without adverse side effects on the environment and agricultural production, and aim for optimizing the fertilizer N dosis according to the crop requirements, or "equilibrium fertilization". The plant requirements may vary with soil type, type of crop and month of the year. Soil and plant testing, in combination with reasonable crop yields, can be used to determine the need of plants (option h.3 and h.5). The use of fertilizer N could be corrected for other sources of N such as atmospheric deposition (option h.4). Fertilizer application could be timed, to make sure that N is available when plants need it. This could be improved by split fertilizer application (option h.6) and slow-release fertilizers (option h.7). Slow-release fertilizers can not be used for all crops. More efficient fertilizer use could be promoted by formulating *codes for good agricultural practices* (Granli and Bockman, 1994). Economic incentives can also stimulate more efficient fertilizer use.

Injection of fertilizer instead of fertilizer surface application may improve fertilizer efficieny (option h.8), but the effect on N_2O emissions may be counteracted by an increase in N_2O production per kilogram fertilizer applied (see option h.1). Therefore this is not a first choice option.

Nitrification inhibitors have been proposed as another possibility to reduce N_2O emissions (e.g. Mosier, 1994). Romançzak (1994) reviewed literature about effects of nitrification inhibitors on N_2O emission. Nitrification inhibitors (option h.9) do not have priority as an option for reducing N_2O emissions, because (i) they have not yet been tested thoroughly in the field in the Netherlands, (ii) when the fertilizer-N is not taken up by crops before the inhibitor is decomposed, they only delay N_2O production instead of actually reducing it, and (iii) their (adverse) environmental side-effects on soil life, surrounding soils, and people are not clear.

- *(h.10 - h.12) Other options.* Other options include (i) keeping soil nitrate concentrations low outside the growing season and (ii) encourage return of wastes to the soil and thus reducing the need for new N inputs (Granli and Bockman, 1994). This could be realized by maintainance of continous plant cover on fields to reduce nitrate leaching, a deployed technology. Incorporation of N-containing crop residues into the soil could be best delayed until just before the next sowing. Also the ploughing of permanent grassland followed by a fallow period is to be avoided. The potential reducttion by these options is estimated at 20% (option h.10). Emissions of N_2O from pasture could be reduced by adjusting the intensity of pasture management to a level at which no nitrate leaches to the groundwater (option h.11).

Emissions of N_2O that are related to manure can be reduced effectively by reducing the amount of manure N produced (option h.12). This reduces not only nitrogen inputs to soils, but also N_2O emissions from stables and storage of manure. Export of manure reduces emissions of N_2O from soils, but not those from stables and storage, while greenhouse gas emissions associated with transport increase.

Per capita meat consumption in industrialized countries can be reduced without adverse health effects. This results in a decrease in livestock numbers. However, an increase in vegetarianism in the Netherlands alone would not have a direct effect on livestock numbers in the country, because most meat is exported.

Several authors claim that N_2O losses are related to the type of fertilizer (e.g. Eichner, 1990). This could lead to recommendations with respect to type of fertilizers that limit N_2O emission. De Groot et al. (1994), for instance, recommends the use of nitrate-based fertilizers when the weather condition is dry. And observations by McTaggert et al. (1994) may lead to the conclusion that ammonium-type of fertilizers yield the lowest emissions of N_2O, when soils are moist. These examples show that the amount of N_2O produced is not determined by type of fertilizer alone. In fact, it can be doubted whether general conclusions can be drawn at all. Reviewing all data available, Bouwman (1994) concluded that the variability in agricultural systems is too great to calculate emission factors for each fertilizer type. Thus on the basis of current knowledge no recommendation regarding specific fertilizer types can be made.

When used as fertilizer, animal manure gives rise to N_2O losses similar to those observed for synthetic fertilizers. But these are not the only fertilizer-related emissions. During the production of synthetic fertilizers, considerable amounts of CO_2 and N_2O are emitted. On the other hand, production of livestock food (partly outside the Netherlands) is a source of CO_2 and N_2O, while cattle also emit CH_4. Thus synthetic and organic fertilizers are not easily compared. Nevertheless, it is clear that in the Netherlands a more efficient use of animal manure as fertilizer will reduce the use of synthetic fertilizers and total N_2O loss as well.

Options to reduce emissions from storage of manure (options i.1 - i.6)

During storage of animal manure N_2O can be formed. Options to reduce these emissions include: (i.1 - i.3) a shift towards "class 1" types of storage, and (i.4 - i.6) some other options.

- *(i.1 - i.3) A shift towards "class 1" types of storage.* N_2O emissions are lowest during anaerobic storage, which is common in the Netherlands. A shift towards anaerobic storage (option i.1) is not needed and no N_2O reduction can be achieved by this option. Future emissions of N_2O can be prevented by avoiding deep-litter stables (option i.2), which are not common in the Netherlands yet. Deep-litter stables are potentially low-NH_3 types of stable from which N_2O emissions can be relatively high. Similarly, addition of HNO_3 to manure to limit NH_3 emissions is a potential source of additional N_2O which could be avoided (option i.3). Nitric acid addition is also not common yet in the Netherlands. The additional N_2O formed is from the nitrate added, not from the manure N (see 4.3.1.1). Thus addition of another acid (e.g. H_2SO_4) would probably not give rise to N_2O formation.

However, possible adverse side effects thereof need further investigation. Concluding, a shift towards "class 1" is hardly possible in the Netherlands, but avoiding a shift towards higher emission classes can prevent future emissions of N_2O.

- *(i.4 - i.6) Other options.* Dillution of urine by increasing water consumption may reduce the amount of nitrogen lost as N_2O from urine patches, because this decreases the N concentration in urine. Although never measured, the potential reduction of this is estimated at 10% (option i.4). It is a demonstrated option, also used to abate scorching, but not common in the Netherlands. Low-nitrogen fodder could reduce the nitrogen content of animal manure (option i.5). This is existing policy in the Netherlands. Finally, manure-related emissions are lowered when less manure N is produced in the Netherlands (option i.6, see also h.11 in Table 5-4).

j. Options to reduce emissions due to NH_3 deposition

Emissions of NH_3 are a source of N_2O, originating in (i) deposition of NH_4^+ on soils which increases biogenic N_2O production, and (ii) the polluted atmosphere, where N_2O may be formed from NH_3. A reduction in NH_3 emissions indirectly reduces these N_2O emissions. Animal waste is the major source of NH_3 in the Netherlands. There are technologies to reduce NH_3 emissions that tend to increase N_2O formation from fertilizers and manure. These are manure injection, deep-litter stables and addition of nitric acid to manure. Method II assumes that the increase in soil emissions due to injection exceeds the reduction in N_2O emissions as a result of NH_3 emissions. Future N_2O emissions could be avoided by resticting fertilizer injection to organic fertilizers (no injection of synthetic fertilizers), and by avoiding deep-litter stables and treatment of manure with nitric acid. Other techniques to reduce NH_3 emissions decrease N_2O losses.

k. Options to reduce emissions due to biological N_2 fixation

Biological fixation of N_2 by legumes is a source of N_2O for which no emission reducing technologies exist. It should be realized, however, that the N_2O emissions involved are assumed to be low relative to, for instance, those induced by fertilizer injection.

l. Options to reduce emissions due to nitrogen leaching

The N_2O emissions after N-leaching can only be reduced by avoidance of leaching. Agricultural nitrogen is a major source of anthropogenic N in groundwater and surface water. Leaching can be minimized by reducing the nitrogen input into soils (options h.3 - h.10). It can be assumed that if fertilizer use (both synthetic and organic) is reduced by 65%, that eventually leaching of fertilizer nitrogen reduced simultaneously. Current policy may reduce the N input to Dutch soils by 55% and N leaching by about 50% (Appendix 6-4). It is assumed here that a 65% reduction in N input reduces N leaching by 55%.

Conclusion

Different options to reduce N_2O emissions from agriculture are identified. However, in the Netherlands there are virtually no feasible options to reduce the N_2O emissions per kg synthetic and organic fertilizer. Therefore, the most effective way to reduce Dutch N_2O emissions is to reduce N input into Dutch soils. There are several ways to achieve this: firstly, by improved fertilizer efficiency, balancing of crop uptake and fertilizer dosis.

Fertilizer N input to Dutch soils will be reduced by 55% relative to 1990 as a result of current policy and can probably be reduce by an additional 10%. This would reduce N_2O production in agricultural soils by leaching losses and NH_3 emissions. Existing policy could be strengthened to stimulate more efficient fertilizer use, for instance, by formulating *codes of good agricultural practice* that adjust N application to crop needs, by promoting slow-release fertilizers, or reducing the amount of manure N produced. The options formmulated do not involve type of fertilizer because it is not possible to draw general conclusions from the data available. Also use of nitrification inhibitors is not considered a feasible option.

Future emissions could be averted by avoiding injection of synthetic fertilizers (option h.1), aerobic storage of manure and deep-litter stables (option i.1, i.3) as well as treatment of manure with HNO_3 (option i.2). These activities with high N_2O emissions are no common practive in the Netherlands yet.

Table 5-4. Overview of options to reduce emissions of N_2O from agriculture, quantifying the technical potential to reduce N_2O emissions (in % of the present emissions per activity) for several options; the table refers to the Dutch situation; the technical potentials may be applicable to most regions in Western European and North America

Option	for reduction of N_2O emission from agriculture	Potential reduction[1]	Market status category of the technology/ Remarks[2]
g	Options to reduce enhancement of background emissions		
g.1	Restore groundwater table in dessicated natural terrain	<10%	deployed / existing policy
g.2	Restore groundwater table in other dessicated terrains	>10%	
h	Options to reduce emissions from fertilizers and manure used		
	A shift towards low-emission-factor activities (class 1 emissions)		
h.1	Prefer surface application to injection	n.q.	deployed[6]; not preferable
h.2	Prefer mineral soils to organic	n.q.	not feasible[7]
	Improve fertilizer efficiency by:	>65%	55% by existing policy
h.3	Soil and plant testing to determine nitrogen needs of crop	20%[4]	deployed
h.4	Adjustment of nitrogen additions to nitrogen in atmospheric deposition, irrigation water, manure, fixed by legumes, and nitrate stored in the soil profile	n.q.	deployed
h.5	Adjustment of nitrogen addition to reasonable crop yield goals	n.q	deployed
h.6	Split fertilizer application to improve timing of N input to match crop growth	n.q.	deployed
h.7	Use of slow-release fertilizers to improve timing of N input to match crop growth	30-65%[4,5]	deployed
h.8	Placement of fertilizers in soil to improve uptake efficiency and reduce losses	n.q.	deployed; not preferable[3] deployed; not preferable[8]
h.9	Nitrogen transformation inhibition by adding nitrification inhibitors to ammonium types of fertilizers (to limit NH_3, N_2O and N_2 volatilization and nitrate accumulation)	<70%[4,11]	
	Other		deployed
h.10	Maintenance of continuous plant cover on fields to reduce nitrate accumulation.	20%[4]	
h.11	Adjusting pasture management intensity	n.q.	
h.12	Reduce manure production (e.g. promote vegetarianism)	n.q.	
i	Options to reduce other N_2O emissions from animal manure storage		
	A shift towards low-emission-factor activities (class 1 emissions)		deployed
i.1	Prefer anaerobic storage of manure to aerobic	0%[9]	deployed
i.2	Avoid nitric acid treatment of manure during storage	0%[9]	deployed
i.3	Avoid deep-litter stables	0%[9]	
	Other		demonstrated
i.4	Increase drinking by grazing livestock (dillution of urine)	10%[11]	deployed; existing policy
i.5	Low-nitrogen fodder for livestock	n.q.	
i.6	Reduce manure production (e.g. promote vegetarianism)	n.q.	
j	Options to reduce emissions due to NH_3 deposition		demonstrated[10]
j.1	Further reduction of NH_3 emissions from stables	n.q.	demonstrated[10]
j.2	Low NH_3 application of fertilizers and manure to soils	n.q.	
k	Options to reduce emissions due to biological N_2 fixation		
l	Options to reduce emissions due to nitrogen leaching		see h.3 - h.9
l.1	More efficient use of fertilizer	>55%[12]	

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[1] Options are based on Mosier and Bouwman (1993); theoretical technical potential to reduce 1990 emissions (%); n.q. = not quantified; [2] Category refers to technology involved; see Table 5-1; "existing policy" refers to the Netherlands; [3] This may reduce fertilizer need but still result in extra N_2O emissions (Table 4-9); [4] Romançzak, 1994; [5] Bouscaren et al., 1993; [6] Increases NH_3 emissions, therefore not considered a preferable option here; [7] This is hardly ever a choice; [8] Not preferable because of adverse side-effects; [9] Aerobic storage, nitric acid addition and deep-litter stables are not common in the Netherlands; [10] Technologies such as injection of manure, deep-litter stables and nitric acid addition result in a net increase in N_2O emission; [11] Uncertain estimate; [12] as a result of a reduction in fertilizer N input by 65%

5.5 Reduction of N_2O emissions from waste

Options to reduce N_2O emissions are formulated for (m) municipal solid waste (MSW) incineration, (n) sewage treatment, and (o) landfills (Table 5-5). In general, waste prevention and recycling of waste are options to reduce N_2O emissions related to waste. Other options to reduce N_2O emissions are listed below.

- *(m.1 - m.2) MSW incineration.* Concentrations of N_2O in flue gases of waste incineration plants are usually lower than 3 ppmv (Spoelstra, 1993; Oonk, pers.comm.). The burning temperature of these combustors is usually within the range of 800 - 1100 °C. The N_2O emitted is formed in local regions of lower temperatures. The most effective way to reduce N_2O emissions from MSW incineration is by improving the combustion process to avoid regions of low temperature (option m.1). This can reduce N_2O emissions by at least 10%. According to the incineration guidelines Dutch incinerators must maintain temperatures of 850 °C for at least two seconds in an afterburning process. This is not high enough for N_2O dissociation, which occurs at 950 °C. An increase of the afterburning temperature to 950 °C would be an effective option to avoid N_2O emissions. The N_2O production can be avoided by reducing the (N-content of) MSW to be incinerated (option m.2). The latter could result from waste prevention, recycling of waste, and digestion or gasification of waste.

In about one-third of Dutch MSW incinerators NOx reduction by SNCR techniques using NH_3 will be implemented in the near future. SCR techniques would result in less formation of N_2O (see stationary combustion).

- *(n.1 - n.2) Sewage treatment.* Most sewage treatment plants are optimized for N removal. Whether N disappears as N_2O or N_2 is not considered. Optimizing the N removal process to N_2 production rather than N_2O production could reduce N_2O emissions by at least 50% in Dutch sewage treatment plants (BKH, 1994) (option n.1). Although this options needs further research, a 50% reduction is assumed achievable in most existing plants, within the coming decade. Another option to reduce N_2O emissions from sewage treatment plants would be a reduction in N removal. However, Dutch policy aims at increased N removal from sewage in order to minimize N input to surface waters. Thus the only way to reduce N removal is by reducing the N in influent. This could be achieved by minimizing the N content of sewage (option n.2), which may be difficult for households.
- *(o.1 - o.2) Landfills.* Although landfills are probably small sources of N_2O, all nitrogen dumped is eventually subject to nitrification or denitrification. Therefore, reducing the amount of nitrogenous compound dumped in landfills will reduce N_2O formation (options o.1, o.2). This can be achieved by recycling organic waste. When recycling results in decreased fertilizer use, overall N_2O emissions will also decrease.

Table 5-5. Overview of options for reduction of N_2O emissions from waste, quantifying the technical potential to reduce N_2O emissions (in % of the present emission per activity) for several options

	Option for reduction of N_2O emission from waste	Potential reduction[1]	Market status category of technology[2] / Remarks
m	Municipal solid waste incineration		
m.1	Optimize burning temperature	50 (10-80)%	demonstrated; <2000
m.2	Minimize (N content of) waste to be burned	n.q.	prospective-deployed
n	Sewage treatment plants		
n.1	Optimize denitrification process	>50%	conceivable; <2000
n.2	Minimize N content of sewage		
o	Landfills		
o.1	Reuse organic waste as fertilizer	n.q.	deployed[3]
o.2	Minimize (N content of) waste to be dumped	100%	deployed

[1] Theoretical potential to reduce 1990 emissions (%); n.q. = not quantified; [2] Category refers to technology involved; see Table 5-1; [3] Leads to a reduction in N_2O emissions by reduced need for synthetic fertilizers

5.6 Reduction of other N_2O emissions

The category "other" includes (p) atmospheric formation of N_2O in NH_3 and NOx polluted atmosphere, (q) biogenic N_2O formation induced by non-agricultural nitrogen loading to surface waters, and (r) global-warming-induced emissions (Table 5-7).

- *(p.1 - p.2) Atmospheric formation of N_2O.* Formation of N_2O in the polluted atmosphere can be decreased by reduction of NOx and NH_3 emissions. This is existing policy in several countries suffering from acidification. However, not all technologies to reduce NOx and NH_3 may decrease net emissions of N_2O. Options to reduce emissions of N_2O, NOx, and NH_3 simultaneously involve energy saving, increased energy efficiency and the use of non-fossil fuel.
- *(q.1 - q.2) Non-agricultural N loading to surface waters.* When the N input to waters decreases, N_2O emissions decrease accordingly. However, if this is accompanied by an increase in N removal in sewage treatment plants that are not optimized, the net effect on N_2O emissions may be an increase.
- *(r.1) Global-warming-induced emissions.* Global-warming-induced N_2O emissions can only be avoided by decreasing emissions of all greenhouse gases.

Table 5-6. Overview of options for reduction of N_2O emissions from waste, quantifying the technical potential to reduce N_2O emissions (in % of the present emission per ectivity) for several options

Option for reduction of N_2O emission from waste		Potential reduction[1]	Market status category of technology[2] / Remarks
p	Formation of N_2O in NOx and NH_3 polluted atmosphere		
p.1	Reduce NOx emission (see c.1 - c.4)	n.q.	deployed[3]
p.2	Reduce NH_3 emission (see j.1 - j.2)	n.q.	deployed[3]
q	N_2O from non-agricultural N loading to surface waters		
q.1	Reduce industrial nitrogen loading	n.q.	deployed[3]
q.2	Reduce atmospheric deposition of NOx and NHx (see p)	n.q.	deployed[3]
r	N_2O emissions from global warming		
r.1	Reduce emissions of all greenhouse gases	n.q.	

[1] Theoretical technical potential to reduce 1990 emissions (%); n.q. = not quantified; [1] Category refers to technology involved; see Table 5-1; [3] The technologies involved may result in a net increase in N_2O emissions

5.7 Conclusion

In this chapter a general overview of options to reduce N_2O emissions is given, and conclusions are drawn for the Dutch situation. Table 5-7 summarizes the feasible options for reducing N_2O emissions in the Netherlands, and the options that are selected for the *additional policy* projections in chapter 6. For several options the potential to reduce emissions is quantified: this includes currently available options and the options that can be expected implementable by 2000. Options in agriculture and mobile combustion that increase emissions of acidifying compounds NOx and NH_3 are not included.

For energy-related emissions of N_2O a few technological options to reduce emissions can be formulated. In stationary combustion N_2O emissions per GJ may be reduced by an estimated 10% by improved combustion in older power plants. In FBC considerably higher reductions, up to 90%, are possible, but FBC is not commonly applied in the Netherlands. These two options have a technical potential to reduce Dutch N_2O emissions from stationary combustion by about 15%. In transport a reduction of N_2O emissions per vehicle-kilometer driven by improvement of 3-way catalysts does not seem feasible in the short term by improving catalysts. Whether avoidance of catalyst aging by early replacement depends on the rate at which aging proceeds, and needs further investigation. If development of a low-N_2O (3-way) catalyst seems feasible in the future, it would effectively reduce N_2O emissions from traffic. From the above may be clear that technologies presently available have a limited potential to reduce N_2O emissions from Dutch energy use. This is partly due to NOx abatement technologies, which tend to increase formation of N_2O. Therefore, energy-related N_2O emissions may, at least in the short term, be more effectively abated by actions leading to reduced fossil fuel use.

Industrial emissions of N_2O can theoretically be reduced considerably. In nitric acid production N_2O emissions could be reduced by 80% by catalytic reduction of N_2O, and by process optimization. These options could reduce total Dutch industrial emissions by 70%, and account for at least half of the technical potential to reduce total Dutch 1990 emissions. A catalytic reduction step is considered a conceivable technology, which could well be technically available before the end of the century; however, this would require further research and developmenr.

The most effective way to reduce N_2O formation in agriculture seems to be decreasing the amount of nitrogen input to soils. This can be achieved by improving the efficiency of fertilizers, which is an existing policy goal. A further reduction of synthetic fertilizer use by 10%, reducing total N input to agricultural soils by an extra 5%, is assummed feasible. In addition, emissions of N_2O from especially organic soils could be reduced by averting dessication. The estimated technical potential of these options to reduce 1990 emissions from Dutch agriculture is about 35%, most of which is realized by existing policy. Future emissions of N_2O could be prevented by avoiding NH_3 reducing activities, such as deep-litter stables for pigs and HNO_3 (nitric acid) treatment of manure.

Emissions of N_2O from waste incineration plants may be technically avoidable by improving the combustion process. Emission from sewage treatment can be reduced by optimizing the treatment process. It is assumed here that these emissions can be reduced by 50%. Prevention of waste, and recycling may be effective ways to reduce emissions of N_2O.

Summarizing, a number of feasible technical options to reduce N_2O emissions could be formulated. The theoretical potential of these options to reduce Dutch 1990 emissions is 40% (i.e. if the technologies were implemented in 1990 without other changes). In chapter 6 will be shown that from 2000 emission could be about 25% lower than in 1990 by the selected options, or about 30% lower than in the *current policy (MV3a)* projections. The largest reductions may be achieved in industry. Other emissions of N_2O may be more effectively reduced by for instance by improvement of energy efficiency, a shift towards renewable sources of energy, a further reduction of nitrogen input into Dutch soils, prevention of waste and recycling of waste materials.

Table 5-7. Theoretical potential to reduce 1990 emissions in the Netherlands, and overview of options to reduce N_2O emissions that are used for the additional policy projections in chapter 6[1]

		Theoretical potential to reduce 1990 emissions[2]		Options used in the *additional policy* projections (chapter 6)	Market status category of the technology[4] / Remarks
		%	Gg N	Emission reduction (%)[3]	
	Energy				
a	*Stationary combustion*	*15% (a.1 - a.4)*			
a.1	Avoid local temperature drop by improvement in combustion process, modified/optimized combustors	>10%	>0.06	10%	prospective/conceivable
a.3-a.4	Apply afterburning or catalytic reduction in FBC	90%	0.04	90%	demonstrated/prospective
a.7-a.8	Switch from coal to oil to gas to renewables	>90%	>0.53	-	deployed
a.9-a.10	Increase energy efficiency, energy saving	n.q.	n.q.	-	
b	*Mobile combustion*				
b.5-b.8	Reduce automobility, switch to non-fossil energy sources, increase energy efficiency, energy saving	n.q.	n.q.	-	
c	*NOx deposition*				
c.2	Increase energy efficiency, energy saving	n.q.	n.q.	-	
	Industries	**70%**			
d	*Adipic acid production*				
d.1-d.3	Apply incineration or catalytic reduction	>98%	0.00	-	deployed; but no adipic acid is produced in the Netherlands
e	*Nitric acid production*				
e.1-e.2	Apply catalytic reduction and improve process	>80%	>8.39	80%	conceivable
	Agriculture	**35%**[5]			
g	*Enhanced background emissions*				
g.1-g.2	Restore groundwater table	>10%	>0.30	10%	deployed; partly existing policy
h	*Fertilizer-induced emissions*				
h.3 - h.7	Decrease fertilizer use by improved fertilizer efficiency (e.g. soil testing; slow-release fertilizers)	>65%	>4.96	5%[6]	deployed; 2015 N input is 55% lower than in 1990 in MV3a/NMP-2 projections
l	*Leaching-induced emissions*				
h.3 - h.7	Decrease fertilizer use by improved fertilizer efficiency	>55%	>1.01	5%[7]	deployed; 2015 N leaching is 50% lower than in 1990 in MV3a/NMP-2 projections

Table 5-7 continued

		Theoretical potential to reduce 1990 emissions[2]		Options used in the *additional policy* projections (chapter 6)	Market status category of the technology[4] / Remark
		%	Gg N	Emission reduction (%)[3]	
	Waste	**50%**			
m	*MSW incineration*				
m.1	Optimizing combustion temperature	10-80%	>0.01	50%	demonstrated
n	*Sewage treatment*				
n.1	Optimize denitrification process	50%	0.13	50%	conceivable
	Total	>40%	>15	25% relative to 1990[7]	

[1] See chapter 6.3; n.q. = not quantified; [2] Reduction in emission per activity (% or Gg N) if technology were fully implemented in 1990 and nothing changed; see also Tables 5-2 to 5-6; [3] Technical potentials of options as used in the additional policy projections in chapter 6, in % per activity, relative to current policy (MV3a) or *National Environmental Policy Plan 2* (NMP-2); [4] Category refers to technology involved; see Table 5-1; [5] Agricultural emissions may be reduced by 35% as a result of NMP-2 measures and an additional 10% reduction in fertilizer use; [6] Nitrogen input in Dutch soils will be reduced by 55% relative to 1990 when *National Environmental Policy Plan 2* (NMP-2) is implemented (see Appendix 6-4); in the *additional policy* projections it is assumed that synthetic fertilizer use can be reduced by an additional 10%; if also animal manure would be reduced by an additional 10% the total N input to soils would be reduced by 65% relative to 1990 (Table 5-4); [7] Nitrogen leaching from Dutch agriculture will be reduced by about 50% relative to 1990 when the NMP-2 is implemented (see Appendix 6-4); in the *additional policy* projections it is assumed that a 55% reduction can be achieved by an additional reduction in synthetic fertilizer use of 10%; [7] In the *additional policy* projections Dutch N_2O emissions are 29-32% lower than in the *current policy projections* (MV3a), 28-30% lower than in the NMP-2 projections, or about 25% lower than in 1990 (see chapter 6; Table 6-12)

6 PAST AND FUTURE N_2O EMISSIONS

6.1 Introduction

This chapter presents projections for global emissions (6.2) and Dutch emissions for the period 1980 - 2015 (6.3). Global emissions for the period 1900 - 1990 are presented in chapter 3.4.2.

6.2 Projections for global N_2O emissions and possible goals

6.2.1 Projections for global emissions

Global emissions of N_2O most probably keep increasing, and anthropogenic emissions could more than double during the next century. In "business-as-usual" scenarios, global emissions increase by 4 - 7 Gg N y^{-1} between 1990 and 2050, and by 4 - 13 Gg N y^{-1} bewteen 1990 and 2100 (Houghton et al., 1992; Kreileman and Bouwman, 1994; Kroeze, 1994a; Nevison, 1994; De Vries et al., 1994). Emissions related to human food production and transport increase relatively fast as a result of a growing world population, and the introduction of 3-way catalytic converters in vehicles.

Global emissions of N_2O keep increasing, even in scenarios assuming severe emission control. However, there may be regions where a reduction in total N_2O emissions is possible. These are industrialized countries without a rapidly growing population. Some studies indicate that total European N_2O emissions could be reduced by 4 - 50% within 10 - 25 years (Bouscaren et al., 1992; Kroeze, 1994b).

6.2.2 Possible goals for N_2O emissions

The Dutch government has subscribed to a long-term international quiality target, calling for the *stabilization of greenhouse gas concentrations in* CO_2*-equivalents at a level well below doubling of the pre-industrial concentrations*, as described in a Dutch climate policy document (Memorandum on Climate Change, or "Nota Klimaatverandering", VROM, 1991). Such a scenario implies a globally averaged temperature increase of about 0.1 °C per decade during the next century (Houghton et al., 1992, Swart, 1994).

The Dutch memorandum on climate change states that the Netherlands will make a reasonable contribution towards achieving abovementioned international objective. The Netherlands also signed the United Framework Convention on Climate Change, the ultimate objective of which is to achieve *a stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system; such a stabilization should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.* The developed country parties commit themselves specifically to demonstrate in their national policies that they are taking the lead in modifying longer-term trends in emissions.

About 4% of the present-day radiative forcing is caused by N_2O (Houghton et al., 1992). It has been calculated that stabilization of the N_2O contribution to a 0.1 °C decadal warming at 4%, requires a reduction of anthropogenic global emissions of about 60%, to 2.4 Tg N y^{-1}, within 25 years (Table 6-1). An additional stabilization of the N_2O concentration from 2100 would require a reduction of almost 80%. The underlying calculations assumed that the climate sensitivity is 3 °C for a doubling of atmospheric CO_2. However, since the sensitivity of the climate to radiative forcing is relatively uncertain, Krause et al. (1989) argued to base risk-minimizing targets on the higher end of the current range of climate sensitivities. This would lead to further reductions than 80%.

Limiting the rate of warming to 0.1 °C may avoid major risks of climate change. However, it is no guarantee for prevention of adverse negative effects, because (i) not all ecosystems may be able to adapt to such a warming, (ii) associated changes in climate and, for instance, storms may still have their impact on human society and (iii) it is not certain where future warming will exceed the global average of 0.1 °C per decade, and where it will be less, which might be especially important for relatively vulnerable ecosystems (Krause et al., 1989; Kroeze, 1993). Scenarios resulting in warming rates lower than a decadal 0.1 °C, or a stand-still of climatic forcing, require reductions in global anthropogenic N_2O emissions in the order of 90 - 100% (Table 6-1).

Reducing global anthropogenic emissions by 60 - 100% within 25 years, implies a limited budget for future emissions. The contribution of a country or a world region to these emissions can be determined by the use of several criteria (Fujii 1990; den Elzen, et al., 1992; Janssen et al., 1992). When economic and population growth in less-developed world regions is taken into consideration, allocation of a limited budget could lead to reductions for industrialized countries that are larger than the global 60 - 100% (Kroeze, 1994b).

Table 6-1. Implication of several climate goals for global N_2O emissions

Climate goal	Global anthropogenic emission (Tg N y^{-1})[1]	Reduction of anthropogenic 1990 emissions (%)[2]
Restoration of pre-industrial situation	0	100
Stand still:		
- stabilization of present temperature	0.3	95
- stabilization of present radiative forcing by N_2O	0.8	87
- stabilization of present atmospheric N_2O concentration	0.8	87
Limiting global warming:		
- stabilizing 2100 concentration after 0.1 °C per decade; 4% by N_2O	1.4	77
- limiting warming by N_2O to 4% of 0.1 °C per decade until 2100	2.4	61[3]

[1] Kroeze, 1994a; assuming, amongst other things, a sensitivity of the earth's climate to radiative forcing equal to 3 °C for a doubling of atmospheric CO_2; a 170-year atmospheric lifetime of N_2O; [2] 1990 anthropogenic emission: 6.1 Tg N y^{-1} (Table 3-3); [3] this is a stabilization of anthropogenic emissions to be realilized within 25 years; the other reductions in the table are to be realized as soon as possible

6.3 Projections for Dutch N_2O emissions (1980 - 2015)

6.3.1 Scenario description

For future emissions for the period 1990 - 2015 the well-documented "European Renaissance" scenario is used, assuming different levels of control:

1. *MV3a.* An update of scenario "European Renaissance" of *National Environmental Outlook 3* (RIVM, 1993a). MV3a can be regarded as *current policy*, including measures for which government decisions are expected before 1-1-1995.

2. *NMP-2, or National Environmental Policy Plan 2.* The NMP-2 projections include measures formulated in the NMP 2, for which government decisions will be taken after 1-1-1995 (R, A, and B measures of NMP-2; RIVM, 1993b).

3. *AP, or additional policy.* The additional policy projections include additional measures that are to be taken by the Dutch government after due investigation (C measures of NMP-2; RIVM, 1993b). In addition, measures that are not mentioned in the NMP-2, based on the options to reduce emissions that are formulated in chapter 5 are included.

All emissions are calculated using method II as described in chapter 4.3.

6.3.2 Natural emissions

Natural emissions of N_2O include soils (1.5 Gg N y^{-1}) and atmospheric formation (<0.1 Gg N y^{-1}) (see chapter 4). It is assumed that these emissions are constant for the period 1980 - 2015.

6.3.3 Energy (stationary and mobile combustion)

Activity data
The energy consumption for 1985 - 1992 and the MV3a, NMP-2 and AP projections for the period 2000 - 2010 are summarized in Appendix 6-1 (stationary combustion) and Appendix 6-2 (mobile combustion). Data for NOx emissions are summarized in Appendix 6-7.

Emission factors
Method II emission factors are used (Table 4-12). For mobile combustion, different types of vehicles are distinguished: gasoline/LPG vehicles without catalytic converters and vehicles with (several types of) catalytic converters of several ages and diesel vehicles (Appendix 6-2). For 1980 - 1985 it is assumed that there were no catalytic-converter-equipped gasoline/LPG cars. For 1990 the amount of vehicle-kilometers driven by gasoline/LPG vehicles is a mixture pf kilometers driven in vehicles with or without, new or old, closed- or open-loop catalytic converters (Baas, 1991). The emission factors used for 1991 and 1992 are assumed equal to those for 1990. This may be a good assumption for 1991. In 1992, however, the number of old catalytic converters, emitting considerably more N_2O, has increased relative to 1990/91 (Thomas, pers.comm.). Therefore, the N_2O emissions estimated for 1992 may be underestimated. For the years from 2000, all vehicles are assumed to be equipped with catalytic converters, and 85% of the vehicle-kilometers are assumed to be performed by vehicles having old catalytic converters.

Past emissions
During the 1980s, energy-related emissions of N_2O increased from 3.9 to 5.4 Gg N y^{-1} (Table 6-2). This increase of 36% exceeds the increase in energy use in stationary combustion (3%) and automobility (31%), because use of coal and catalytic-converter-equipped cars increased relatively fast. About two-thirds of the energy-related N_2O emissions are from mobile combustion (Fig. 6-1).

Future emissions: current policy (MV3a)
Emissions of N_2O almost double in the MV3a projections, reflecting implementation of current policy measures. The share of mobile combustion also increases to 84% of the energy-related emissions in 2015. This is not only a result of increased automobility, but also of aging of catalytic converters. In 1990 15% of the kilometers driven in gasoline/LPG vehicles involved cars with old catalytic converters. From 2000 this percentage is 85%. Old 3-way catalytic converters emit about three times as much N_2O as new 3-way catalytic converters.

Future emissions: National Environmental Policy Plan 2 (NMP-2)
National Environmental Policy Plan 2 includes measures that reduce energy use and automobility. Implementation of these measures results in calculated N_2O emissions that are 7% lower than the MV3a projections. This is mainly the result of reduced car use through economic incentives to encourage travel by public transport.

Future emissions: additional policy (AP)

Additional policy could reduce N_2O emissions from stationary combustion by about 15% relative to the NMP-2 projections (Fig. 6-1 and Table 6-3), which is not sufficient to stabilize emissions at their 1990 level. Two technical options are considered: optimization of the combustion process in conventional combustors (option a.1) and afterburning of N_2O in fluidized bed combustors (option a.2; Table 5-7).

For mobile combustion and NOx deposition technical options to reduce N_2O emissions are not considered. As a result, additional policies reduce total N_2O emissions from energy only slightly. A 60% reduction of emissions from transportation can be effectively achieved by abolishing the use of 3-way catalytic converters. However, this would increase emissions of NOx, VOC and CO and is therefore not considered a preferable option here. A very effective way to reduce emissions from transport may, however, be a reduction in automobility, but this is not included as an additional policy measure.

Table 6-2. Past N_2O emissions from energy use (Gg N y^{-1}) in the Netherlands estimated with method II

	1980	1985	1990[4]	1991	1992
Stationary combustion[1]	0.6	0.6	0.7	0.7	0.7
Mobile combustion[2]	2.1	2.2	3.4	3.4	3.6
NOx deposition[3]	1.2	1.2	1.2	1.2	1.2
Total	3.9	4.0	5.4	5.4	5.5

[1] Appendix 6-1; [2] Appendix 6-2; [3] Appendix 6-7; [4] Table 4-14, 4-15, 4-16

Table 6-3. Future N_2O emissions from energy use (Gg N y^{-1}) in the Netherlands estimated with method II

		Current Policy (MV3a)			National Environmental Policy Plan 2 (NMP-2)			Additional Policy (AP)		
	1990	2000	2010	2015	2000	2010	2015	2000	2010	2015
Stationary combustion[1]	0.7	0.6	0.8	0.9	0.6	0.6	0.9	0.5	0.5	0.8
Mobile combustion[2]	3.4	7.1	8.1	8.6	6.9	7.6	8.0	6.9	7.6	8.0
NOx deposition[3]	1.2	0.8	0.8	0.8	0.8	0.6	0.6	0.8	0.6	0.6
Total	5.4	8.6	9.7	10.3	8.3	8.7	9.5	8.2	8.7	9.4

[1] Appendix 6-1; [2] Appendix 6-2; [3] Appendix 6-7

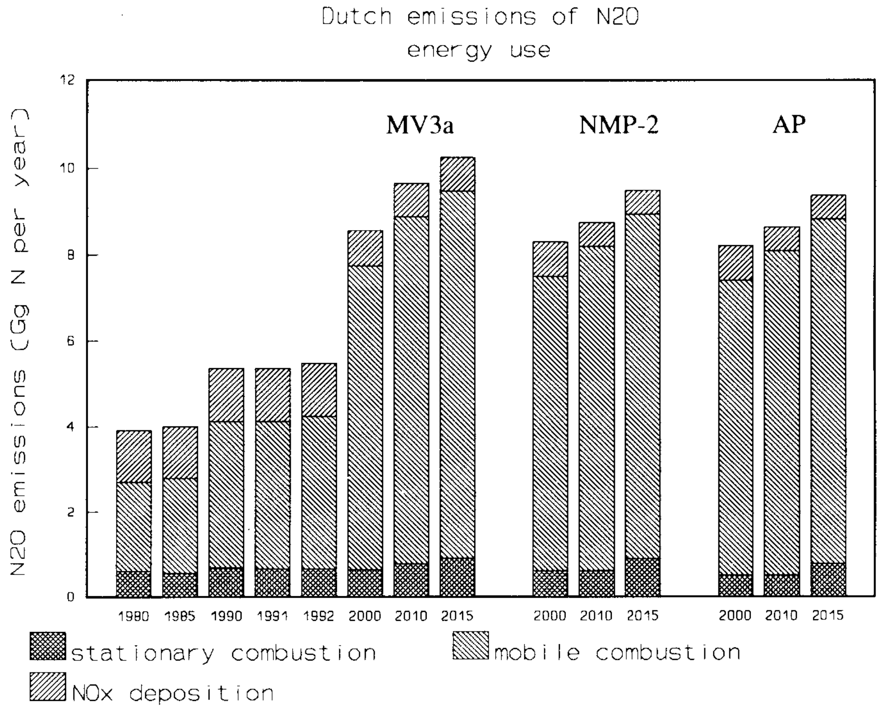

Fig. 6-1. Dutch N_2O emissions from stationary and mobile combustion. MV3a = current policy; NMP-2 = National Environmental Policy Plan 2; AP = Additional Policy

6.3.4 Industry

Nitric acid production
Annual production of nitric acid in the Netherlands is estimated at 617 ton N (Appendix 6-3). This estimate refers to the period 1990 - 1992 and is from the Dutch Emission Registration (VROM, 1993). Nitric acid production in 1980 and 1985 is assumed to be 440 and 545 Gg N y^{-1} (Van Amstel et al., 1994), which may be an underestimation of total production. Future production is based on assumed growth in synthetic fertilizer production in the European Renaissance scenario of *National Environmental Outlook 3* (RIVM, 1993a). Thus for 2000, 2010, and 2015 nitric acid production the assumed increase amounts to 15%, 28%, and 33%, respectively, relative to 1990.

Other chamical industries identified as sources of N_2O in the Netherlands emitted an estimated 1.08 Gg N_2O-N in 1990 (VROM, 1993). The future increase of this source is based here on assumed growth of the petrochemical industry in the same scenario, European Renaissance, implying an increase of 31%, 63% and 78% in 2000, 2010, and 2015, respectively, relative to 1990.

Past emissions
Industrial emissions have been steadily increasing from 8.6 to 11.6 Gg N y^{-1} since 1980 (Table 6-4).

Future emissions: current policy and National Environmental Policy Plan 2 (MV3/NMP-2)
In the MV3a and NMP-2 projections, industrial N_2O emissions keep increasing (Table 6-5).

Future emissions: additional policy
Additional policy could reduce industrial emissions considerably, by 70% relative to the MV3a and NMP-2 projections. This is the result of an assumed catalytic reduction step in combination with process optimization, which could avoid 9.7 - 11.2 Gg N y^{-1} (options e.1 - e.2; Table 5-7). Both options need further development, but by 2000 these options can be technically available. In the additional policy projections it is assumed that even implementation is achievable by 2000. This may be an optimistic assumption, but not impossible. It should be realized here that not only the the assumptions about the implementation of these technologies, but also the emission factors are relatively uncertain and the costs unknown. A further evaluation needed will be done in the near future (Oonk, pers.comm.). However, even if the total industrial source strength has been overestimated greatly, which does not seem likely, the potential reduction in N_2O emissions by a catalytic reduction step in would still be the largest of all additional policy options considered in this study (Table 5-7).

Table 6-4. Past N_2O emissions (Gg N y^{-1}) from industry in the Netherlands estimated with method II

	1980	1985	1990[2]	1991	1992
Nitric acid production[1]	7.5	9.3	10.5	10.5	10.5
Other chemical industry	1.1	1.1	1.1	1.1	1.1
Total N_2O emission	8.6	10.4	11.6	11.6	11.6

[1] Appendix 6-3; [2] Table 4-17

Table 6-5. Future N_2O emissions from other industries in the Netherlands (Gg N y^{-1}) estimated with method II

		Current policy (MV3a)			National Environmental Policy Plan 2 (NMP-2)			Additional policy (AP)		
	1990	2000	2010	2015	2000	2010	2015	2000	2010	2015
Nitric acid production[1]	10.5	12.1	13.4	14.0	12.1	13.4	14.0	2.4	2.7	2.8
Other	1.1	1.4	1.8	1.9	1.4	1.8	1.9	1.4	1.8	1.9
Total N_2O emissions	11.6	13.5	15.2	15.9	13.5	15.2	15.9	3.8	4.4	4.7

[1] Appendix 6-3

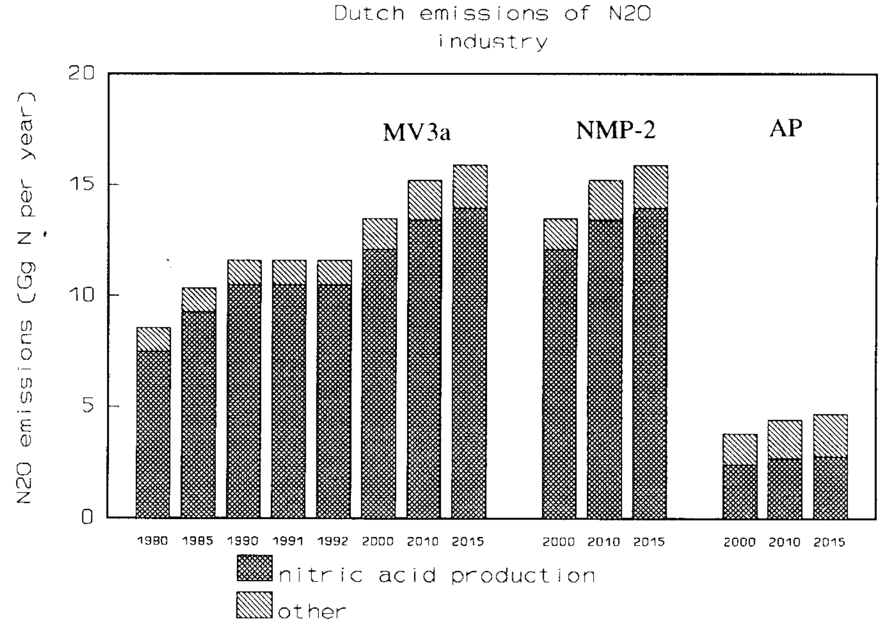

Fig. 6-2. Dutch N_2O emissions from industry. MV3a = current policy; NMP-2 = National Environmental Policy Plan 2; AP = Additional Policy

6.3.5 Agriculture

Activity levels

Appendix 6-4 summarizes the activity data used for agriculture. The projections for MV3a (current policy) and NMP-2 (*National Environmental Policy Plan* 2) are similar, and include the Dutch policy on manure ("derde fase mest beleid") (Van der Hoek, 1994). In order to evaluate the effects of the "derde fase mestbeleid", projections for *National Environmental Outlook 3*, MV3, (RIVM, 1993a) are presented as well here. The MV3a projections show an important decrease in the sum of mineral and organic fertilizers of 10% since 1980, and 55% between 1990 and 2010, as a result of the "derde fase mestbeleid" (Table 6-6).

Past emissions

Between 1980 and 1992 agricultural emissions varied between 16.9 and 18.8 Gg N y^{-1}, without a clear trend (Table 6-6). Thus the 10% decrease in N input to soils did not have an equivalent effect on N_2O emissions. This is partly the result of the introduction of low-NH_3 application of animal manure to soils such as manure injection, which increases the N_2O emissions per kg of manure and has been increasingly used since 1990.

Future emissions: pre-"derde fase mestbeleid" (MV3)

Without the "derde fase mestbeleid" total N input into soils would by 2010 be about 50% lower than in 1990 (Table 6-7). As a result, most agricultural N_2O emissions decrease. However, emissions from manure application to soils as fertilizer remain above their 1990 level, despite a reduction in N excretion by animals. This is the result of an increase in injection as a means of manure application. The calculated net effect of these developments is about 25% reduction in agricultural N_2O emissions between 1990 and 2010.

Future emissions: current policy (MV3a) and NMP-2 (both incl. "derde fase mestbeleid")

As a result of the "derde fase mestbeleid" N input into Dutch soils is further reduced (Table 6-7). Agricultural N_2O emissions are 9% lower than without these policy measures and decrease from 16.9 Gg N y^{-1} in 1990 to 11.5 from 2010.

Future emissions: Additional policy (AP)

The additional policy measures considered decrease future agricultural N_2O emissions by an additional 5% (Table 6-7). The options considered are (options g.1 and g.2) raising of groundwater levels in dessicated terrains, and (options h.3 - h.7; Table 5-7) a 10%-reduction in mineral fertilizer used as a result of improved fertilizer efficiency. Thus a further reduction of N excretion by animals is not considered, although this would have important effects on N_2O emissions. For example, a reduction of manure-N production and mineral fertilizer-N use by another 50%, will reduce N_2O emissions from 10.9 to about 7 Gg N y^{-1}. On the other hand, if 75% of the manure is produced in deep-litter stables (a possible measure to reduce NH_3 emissions), the agricultural N_2O emissions would double to about 21 Gg N y^{-1}, of which about half from stables and storage of manure. Therefore, not implementing deep-litter stables and also HNO_3-treatment is effective in avoiding future N_2O emissions (Table 6-8).

Table 6-6. Past N_2O emissions from agriculture (Gg N y^{-1}) in the Netherlands estimated with method II

	1980	1985	1990[3]	1991	1992
Total N excretion by animals[1]	622	650	585	639	619
Soil N input[2]	861	910	771	793	773
N_2O emissions[4]					
Background emissions[5]	3.0	3.0	3.0	3.0	3.0
Mineral fertilizer use	5.2	5.4	4.4	4.3	4.2
Manure: meadow	2.6	2.6	2.2	2.3	2.2
Manure: stable	0.4	0.4	0.5	0.5	0.5
Manure: used as fertilizer	3.2	3.4	3.2	3.8	4.5
NH_3 deposition	1.9	2.0	1.6	1.7	1.3
Legumes	0.0	0.1	0.2	0.1	0.1
Leaching	1.8	1.8	1.8	1.9	1.8
Total	18.1	18.8	16.9	17.6	17.6

[1] Appendix 6-4, Table A-12; [2] Mineral fertilizer + manure-N; not corrected for NH_3 emissions (see Appendix 6-4; Table A-12); [3] Table 4-18; [4] Method II; see Tables 4-8 and 4-9, and Appendix 6-4, Table A-15; [5] Assumed constant at 1990 level (Table 4-8)

Table 6-7. Future N_2O emissions from agriculture (Gg N y^{-1}) in the Netherlands estimated with method II

		pre-"derde fase mestbeleid" (MV3)			"derde fase mestbeleid" (MV3a; NMP-2)			Additional policy (AP)		
	1990	2000	2010	2015	2000	2010	2015	2000	2010	2015
Total N excretion by animals[1]	585	470	459	459	444	413	413	444	413	413
Soil N-input[2]	771	411	380	380	378	347	346	357	329	329
N_2O emissions[3]										
Background emissions[4]	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.7	2.7	2.7
Mineral fertilizer use	4.4	1.9	1.6	1.6	2.3	1.9	1.9	2.0	1.7	1.7
Manure: meadow	2.2	1.7	1.7	1.7	1.6	1.5	1.5	1.6	1.5	1.5
Manure: stable	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4[5]	0.4[5]	0.4[5]
Manure: used as fertilizer	3.2	4.5	4.5	4.5	3.3	3.3	3.3	3.3	3.3	3.3
NH_3 deposition	1.6	0.7	0.5	0.5	0.6	0.5	0.5	0.6	0.5	0.5
Legumes	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Leaching	1.8	1.2	0.9	0.9	1.2	0.9	0.9	1.1	0.8	0.8
Total	16.9	13.5	12.7	12.7	12.4	11.5	11.5	11.8	10.9[6]	10.9[6]

[1] Appendix 6-4, Tables A-12 and A-13; [2] Mineral fertilizer + manure N; not corrected for NH_3 emission; [3] Method II: Tables 4-8 and 4-9, Appendix 6-4, Tables A-15 and A-16; [4] Assumed constant at 1990 level (Table 4-8); In AP projections dessication abatement (options g.1 and g.2, Table 5-7); [5] Would be about 21 Gg N y^{-1} if 75% of manure was produced in deep-litter stables; [6] Would be about 7 Gg N y^{-1} if manure-N production and fertilizer-N use were reduced by 50%

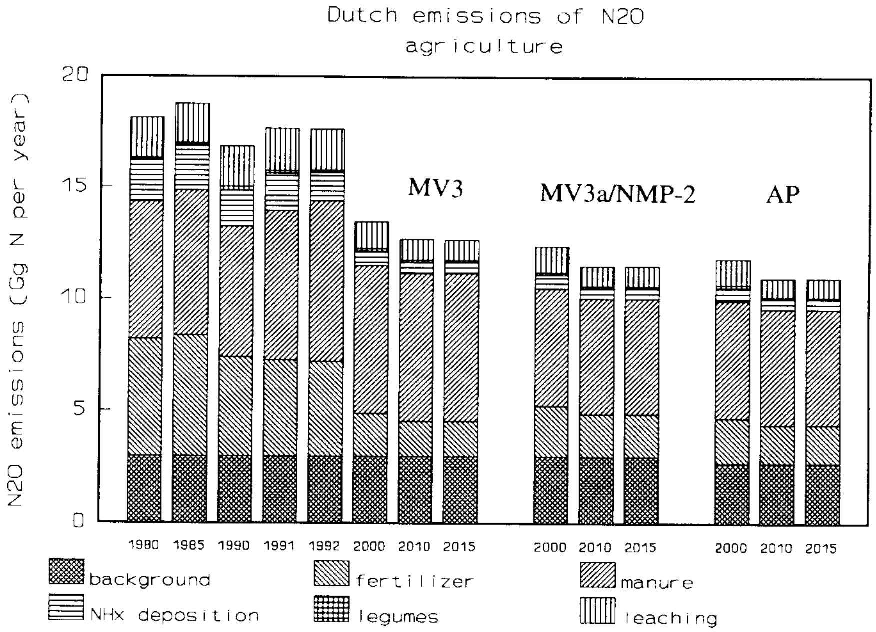

Fig. 6-3. Dutch N_2O emissions from agriculture. MV3a = current policy; NMP-2 = National Environmental Policy Plan 2; AP = Additional Policy

6.3.6 Waste

Activity levels

Between 1980 and 1990 the amount of waste incinerated increased from 1900 to 3,400 10^3 ton of waste per year and is expected to increase to 10,800 10^3 ton by 2015 (see Appendix 6-6). Nitrogen removal by denitrification in wastewater treatment plants, i.e. the difference between N influent and the sum of N effluent and sludge is expected to more than double between 1990 and 2015.

Past emissions

Since 1980 N_2O emissions from waste have increased by about 30%. This is mainly the result of increased N removal from sewage, while MSW incineration is a relatively small source of N_2O in the Netherlands (Table 6-8).

Future emissions: current policy/National Environmental Policy Plan 2 (MV3a/NMP-2)

N_2O emissions from both sewage and waste incineration could more than double during the coming decade. This as a result of Dutch policy goal to increase both N removal from sewage and incineration of waste (Table 6-9).

Future emissions: Additional policy (AP)

The additional policy measures formulated may reduce N_2O emissions from waste by 50% relative to the MV3a and NMP-2 pojections (Fig. 6-4). Nevertheless, the emissions during the next century exceed the 1990 emissions. The measures considered are optimization of MSW incineration (option n.1) and optimization of sewage treatment (option o.1; Table 5-7). Measures not taken into account involve a reduction in the amount of N in waste, waste prevention, and waste recycling.

Table 6-8. Past N_2O emissions from waste (Gg N y^{-1}) in the Netherlands estimated with method II

	1980	1985	1990[2]	1991	1992
MSW incineration[1]	<0.1	<0.1	<0.1	<0.1	<0.1
Sewage treatment plants[1]	0.2	0.2	0.3	0.3	0.3
Total	0.2	0.2	0.3	0.3	0.3

[1] Appendix 6-6 and Tables 4-9 and 4-12; [2] Table 4.19

Table 6-9. Future N_2O emissions from waste (Gg N y^{-1}) in the Netherlands

		Current policy (MV3a)			National Environmental Policy Plan (NMP-2)			Additional policy (AP)		
	1990	2000	2010	2015	2000	2010	2015	2000	2010	2015
MSW incineration[1]	<0.1	0.1	0.1	0.1	0.1	0.1	0.1	<0.1	0.1	0.1
Sewage treatment[1]	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.3
Total	0.3	0.6	0.6	0.7	0.6	0.7	0.7	0.3	0.3	0.3

[1] Appendix 6-6 and Table 4-9 and 4-12

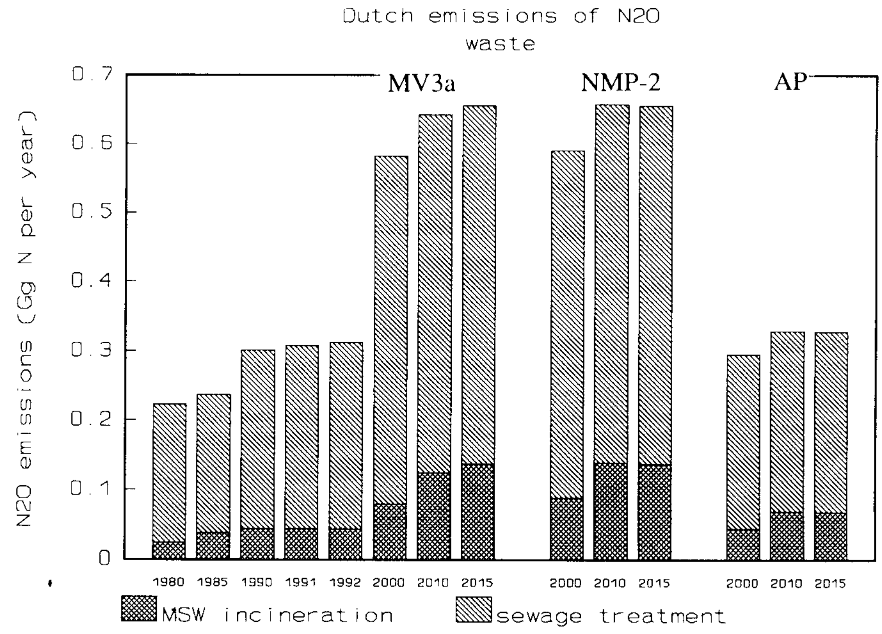

Fig. 6-4. Dutch N_2O emissions from waste. MV3a = current policy; NMP-2 = National Environmental Policy Plan 2; AP = Additional Policy

6.3.7 Other emissions

Activity levels

The category "other" includes atmospheric formation, N inputs into waters from non-agricultural sources, NH_3 deposition other than from agricultural NH_3, NOx emissions from non-energy sources, and anaesthesia (see Appendix 6-6 for the activity data). For future use of N_2O in anaesthesia the figures for growth in nitric acid production have been adopted (see 6.3.4).

Past emissions

"Other" N_2O emissions have been decreasing since 1980, mainly as a result of policy measures that reduce N input into surface waters (Table 6-10).

Future emissions: MV3a/NMP2

Future N_2O emissions in the category "other" will continue to decrease to 1.1 (MV3a) and 1.0 (NMP-2) Gg N y^{-1} (Table 6-11). This is a result of (1) further reductions in N loading to surface waters, and (2) a further reduction in NH_3 emissions, reducing both formation of N_2O in the atmosphere and biogenic emissions of N_2O induced by N inputs from atmospheric NHx deposition.

Additional policy

No additional policy measures were formulated for these emissions (Fig. 6-5).

Table 6-10. Past N_2O emissions in the category "other" (Gg N y^{-1}) estimated with method II[1]

	1980	1985	1990[2]	1991	1992
Atmospheric formation	<0.1	<0.1	<0.1	<0.1	<0.1
Non-agricultural N-input waters	0.7	0.7	0.6	0.6	0.6
Other NH_3 emissions	0.1	0.1	0.1	0.1	0.1
Other NOx emissions	0.5	0.5	0.5	0.5	0.5
Anaesthesia	0.3	0.3	0.3	0.3	0.3
Total	1.7	1.7	1.6	1.6	1.5

[1] Appendix 6-6 (Table A-23) and Tables A-9 and 4-12; [2] Table 4-20

Table 6-11. Future N_2O emissions in the category "other" (Gg N y^{-1}) estimated with method II[1]

		Current policy (MV3a)			National Environmental Policy Plan 2 (NMP-2)			Additional policy (AP)		
	1990	2000	2010	2015	2000	2010	2015	2000	2010	2015
Atmospheric formation	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Other N-input waters	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Other NH_3 emissions	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other NOx emissions	0.5	0.3	0.2	0.2	0.3	0.1	0.1	0.3	0.1	0.1
Anaesthesia	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	1.6	1.1	1.1	1.1	1.1	1.0	1.0	1.1	1.0	1.0

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[1] Appendix 6-4 (Table A-24) and Tables 4-9 and 4-12

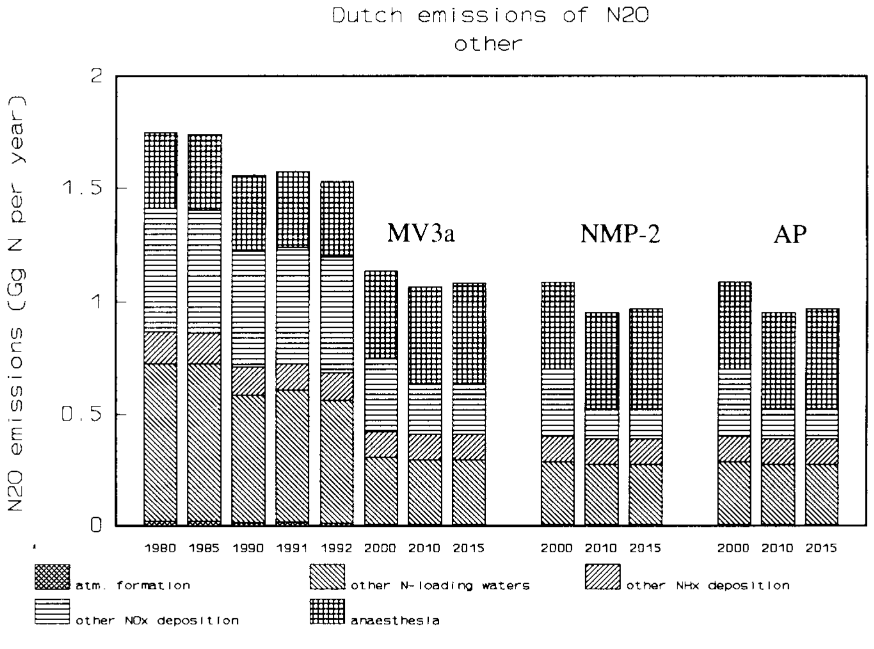

Fig. 6-5. Dutch N_2O emissions from the category "other". MV3a = current policy; NMP-2 = National Environmental Policy Plan 2; AP = Additional Policy

6.3.8 Total Dutch N_2O emissions

Past emissions

Total emissions of N_2O increased from 34.1 in 1980 to 37.1 Gg N y^{-1} in 1990. Most important contributors are agriculture and industry (Table 6-12).

Policy goal

The Dutch policy goal is to stabilize emissions of N_2O at the 1990 level by 2000 (VROM, 1991). Using method II, 1990 emissions are estimated at 37.1 Gg N y^{-1}, or 58.4 Gg N_2O y^{-1}.

Future emissions: current policy (MV3a)

The Dutch stabilization goal is exceeded by the MV3a projections. By 2000, 2010, and 2015 respective Dutch N_2O emissions are 1%, 6% and 10% higher than in 1990. This is a net effect of decreasing agricultural and "other" emissions, and increasing emissions from the other sectors (Table 6-13). Especially N_2O emissions from transport increase, mainly as a result of the introduction of 3-way catalytic converters in cars. It should be noted that the uncertainty in these estimates exceeds the growth rate. However, the largest uncertainties with respect to N_2O involve the emission factors, not the activity data. This implies that the trends in N_2O emissions are relatively certain.

Future emissions: National Environmental Policy Plan 2 (NMP-2)

The measures of *National Environmental Policy Plan 2* reduce the calculated emissions from energy, agriculture and "other". As a result, Dutch emissions are calculated to be less than 1 Gg N y^{-1} lower than the MV3a projections (Table 6-13). This reduction is not sufficient to stabilize next century's emissions at the 1990 level.

Future emissions: Additional policy (AP)

The additional policy measures considered may reduce N_2O emissions to a level of 27.8 Gg N y^{-1} by 2015, a reduction of about 30% relative to the NMP-2 projections, and 25% relative to 1990 (Fig. 6-6). The most important reduction results from implementation of a catalytic reduction step in nitric acid production, which could reduce emissions by more than 11 Gg N_2O-N y^{-1}. A catalytic converter is not available at present. The assumption that implementation of this technology is feasible by 2000 may be optimistic, but not impossible. Without this option to reduce emissions, the calculated Dutch emissions still exceed the 1990 level after the year 2000.

Other reductions are achieved in mineral fertilizer use, sewage treatment, and stationary combustion. Also, most of these technologies are not yet commercially available, but can probably be implemented before the end of the century. A conservative estimate has been made for agricultural emissions. If N input into soils is further reduced, N_2O emissions could be effectively reduced as well.

Table 6-12. Dutch N_2O emissions (Gg N y^{-1}) for the period 1980 - 1990 and MV3a, NMP-2 and AP projections for 2000 - 2015 with N_2O emissions calculated using method II

				Current policy (MV3a)			National Environ. Policy Plan (NMP-2)			Additional policy (AP)		
	1980	1985	1990	2000	2010	2015	2000	2010	2015	2000	2010	2015
Natural	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Energy	3.9	4.0	5.4	8.6	9.7	10.3	8.3	8.7	9.5	8.2	8.7	9.4
-stationary	0.6	0.6	0.7	0.6	0.8	0.9	0.6	0.6	0.9	0.5	0.5	0.8
-mobile	2.1	2.2	3.4	7.1	8.1	8.6	6.9	7.6	8.0	6.9	7.6	8.0
-NOx deposit.	1.2	1.2	1.2	0.8	0.8	0.8	0.8	0.6	0.6	0.8	0.6	0.6
Industry	8.6	10.4	11.6	13.5	15.2	15.9	13.5	15.2	15.9	3.8	4.4	4.7
Agriculture	18.1	18.8	16.9	12.4	11.5	11.5	12.4	11.5	11.5	11.8	10.9	10.9
-background	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.7	2.7	2.7
-mineral fert.	5.2	5.4	4.4	2.3	1.9	1.9	2.3	1.9	1.9	2.0	1.7	1.7
-manure	6.2	6.5	5.8	5.3	5.1	5.1	5.3	5.1	5.1	5.3	5.1	5.1
-other[1]	3.8	3.9	3.6	1.9	1.4	1.4	1.9	1.4	1.4	1.8	1.4	1.4
Waste	0.2	0.2	0.3	0.6	0.6	0.7	0.6	0.7	0.7	0.3	0.3	0.3
Other	1.7	1.7	1.6	1.1	1.1	1.1	1.1	1.0	1.0	1.1	1.0	1.0
Total	34.1	36.6	37.1	37.7	39.5	40.8	37.3	38.5	40.0	26.7	26.8	27.8

[1] N_2O emissions from atmospheric deposition of agricultural NH_3, leaching of agricultural N and legumes

Table 6-13. Change in N_2O emissions between 1990 and 2015 with current policy (MV3a), and effect of National Environmental Policy Plan 2 (NMP-2) and additional policy (AP) on Dutch N_2O emissions (Gg N y^{-1}) in 2015 estimated with method II

	2015-1990 MV3a[1]	Effect NMP2[2]	Effect AP[3]	AP option[4]
Energy	4.9	-0.8	-0.1	
- stationary combustion	0.2	-0.0	-0.1	a.1, a.3, a.4
- mobile combustion	5.1	-0.5	0	
- NOx deposition	-0.5	-0.2	0	
Industry	4.3	0	-11.2	
- nitric acid production	3.5	0	-11.2	e.1, e.2
- other chemical industry	0.8	0	0	
Agriculture	-5.4	0	-0.5	
- background	0	0	-0.3	g.1, g.2
- mineral fertilizer	-2.5	0	-0.2	h.3-h.7
- manure meadows	-0.7	0	0	
- manure stables	-0.1	0	0	
- manure fertilizer	0.1	0	0	
- legumes	-1.2	0	0	
- deposition of NH_3	-0.0	0	0	
- leaching	-1.0	0	-0.0	h.3-h.7
Waste	0.4	0	-0.3	
- MSW incineration	0.1	0	-0.1	m.1
- sewage	0.3	0	-0.3	n.1
Other	-0.5	-0.1	0	
- atmospheric formation	-0.0	0	0	
- non-agric. N-input waters	-0.3	-0.0	0	
- deposition of non-agric. NH_3	-0.0	0	0	
- deposition of non-energy NOx	-0.3	-0.1	0	
- anaesthesia	0.1	0	0	
Total	3.7	-0.9	-12.1	

[1] Difference between projections for 2015 (MV3a) and 1990: 2015 - 1990; [2] Difference between current policy and National Environmental Policy Plan 2 projections for 2015: MV3a - NMP2; [3] Difference between National Environmental Policy Plan 2 and additional policy projections for 2015: NMP2 - AP; [4] See Table 5-7

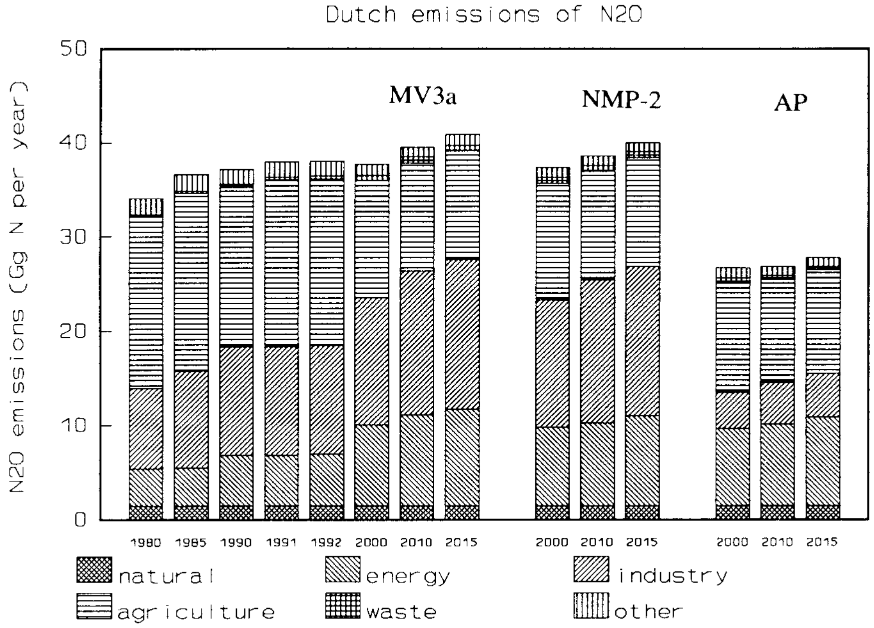

Fig. 6-6. Total Dutch N_2O emissions. MV3a = current policy; NMP-2 = National Environmental Policy Plan 2; AP = Additional Policy

6.4 Conclusions

Scenarios for global emissions indicate that it is likely that global emissions of N_2O will continue to increase. Especially emissions related to food production are difficult to control as long as the world population grows.

In the Netherlands, emissions of N_2O have been increasing, reaching 37.1 Gg N y^{-1} in 1990. Projections for the period 1990 - 2015 are presented for the European Renaissance scenario, assuming different levels of control: current policy (MV3a), *National Environmental Policy Plan 2* (NMP-2) and additional policy (AP). The Dutch policy goal is to stabilize N_2O emissions at their 1990 level. However, N_2O emissions exceed the 1990 level in both the MV3a and NMP-2 projections. In the AP projections N_2O emissions are by 2015 25% lower than in 1990. The largest reduction is achieved in industry, by a catalytic reduction step in nitric acid production. This is also one of the most uncertain options for N_2O reduction, as far as implementation by 2000 is concerned. Without this reduction step stabilization of Dutch emissions at the 1990 level may be difficult to achieve after 2000 without development of yet unknown techniques or reductions in the volumes of activities.

As described in the Dutch policy document on climate change ("Nota Klimaatverandering") the Dutch policy aims at stabilizing CO_2-equivalent concentrations at a level well below doubling of the pre-industrial concentration, which implies a global warming of about 0.1 °C per decade. If, gas-by-gas, the contribution to global warming of 0.1 °C per decade is to stabilize at the present level, anthropogenic N_2O emissions are to be reduced much further than the 25% achieved by the additional technologies considered in the present study.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

7.1.1 Global emissions

It is concluded here, that it is possible to explain the observed trend in atmospheric nitrous oxide (N_2O) by known global sources. The atmospheric concentrations of N_2O have been increasing during the last century. This is clearly observed in the atmosphere. Compilation of published inventories gives a total global emission of 16.9 (9.6 - 27.6) Tg N y^{-1} for 1990, of which 6.1 (1.5 - 13.9) Tg N y^{-1} is anthropogenic. The observed atmospheric concentrations indicate that this may be close to the actual emissions. Thus the estimates of total natural and anthropogenic emissions are relatively certain, but uncertainties exist about the origin of both natural and anthropogenic N_2O. Nevertheless, several estimates have become more certain during the last years.

As described in the "Nota Klimaatverandering", a document on Dutch climate policy, the Dutch policy aims at stabilization of greenhouse gas concentrations in CO_2-equivalents at a level well below doubling of the pre-industrial concentrations. Such a scenario implies a global average temperature rise in the order of 0.1 °C per decade according to the IPCC. If the N_2O contribution to such a warming is to be stabilized at the present level, global anthropogenic N_2O emissions need to be reduced by about 60 - 100% within 25 years. However, "Business as usual" scenarios indicate that global anthropogenic emissions could more than double during the next century. Even in scenarios assuming severe emission control global emissions of N_2O keep increasing, because N_2O emissions, related to human food production for a growing world population are difficult to control. In several industrialized world regions, on the other hand, emissions of N_2O can be reduced considerably.

7.1.2 Methods to estimate Dutch emissions

Emissions of N_2O from the Netherlands are estimated using two methods. Method I is the default IPCC methodology and results in 17 (6 - 38) Gg N y^{-1} of anthropogenic emissions in 1990. Method II is an update of the RIVM methodology, and results in 37 (13 - 70) Gg N y^{-1}, of which 1.5 (0 - 3.0) are natural. The difference between the two methods is a result of (1) the number of sources taken into account, and (2) the emission factor used. Method II is preferred for estimating Dutch emissions, because it accounts for more sources, emission factors are validated with Dutch research, and it is more consistent when applied to global activity data than method I.

7.1.3 Projections for Dutch emissions

The Dutch policy goal is to stabilize emissions of N_2O at their 1990 level. Scenario calculations indicate that additional policy is needed to realize this goal. Future emissions in the Netherlands are presented for the scenario European Renaissance, assuming different levels of control (Fig. 7-1): current policy (MV3a), the National Environmental Policy Plan 2 (NMP-2) and additional policy (AP). Additional policy includes a number of technical options to reduce N_2O emissions.

Current policy and the National Environmental Policy Plan 2

The MV3a projections show that current policy is not sufficient to stabilize Dutch N_2O emissions at the 1990 level (Fig. 7-1). The growth in emissions is the net effect of a decrease in emissions from agriculture, and an increase in emissions from other sectors. The largest increases are found in traffic and industry.

The NMP-2 measures are calculated to reduce the growth in N_2O emission slightly, however, not sufficient to stabilize next century's emissions at the 1990 level. The NMP-2 measures avoid some N_2O emissions as result of reduced growth in energy use and automobility, and a further reduction in excretion of manure-N by Dutch livestock.

Additional policy

A number of technical options to reduce N_2O emissions are described in this document. The technical potentials of these options to reduce Dutch emissions of N_2O have been estimated for stationary combustion (15%), industry (70%), agriculture (35%) and waste (50%). These options have the potential to reduce the 1990 emissions in the Netherlands by about 40%, if nothing else would change (Fig. 7-1). Most of the options formulated for agriculture are already included in the NMP-2. The additional policy measures not included in the NMP-2 may reduce the emissions to 28 Gg N y^{-1} in 2015. This is 12 Gg N y^{-1} (30%) lower than the NMP-2 projections, and 9 Gg N (25%) lower than in 1990. About 90% of the AP reduction is achieved in industry, as a result of a catalytic reduction step in nitric acid production.

The technical options included in the AP projections seem sufficient to realize the policy goal to stabilize Dutch N_2O emissions at their 1990 level. Most of the reduction is achieved by a catalytic reduction step in nitric acid production. However, the implementation of a catalyst in nitric acid production may not be achieved by 2000. Then a stabilization of Dutch N_2O emissions may be possible to achieve by 2000, but not thereafter. Without a catalytic reduction step in nitric acid production, yet unavailable or unknown technologies, or reductions in activities such as N input to soils, automobility and fossil fuel use may be required to maintain next century's emissions at the 1990 level. If the policy objective would include a stabilization of N_2O relative contribution to global decadal warming of 0.1 °C at the present 4%, much larger reductions in Dutch N_2O emissions than achieved in the AP projections may be necessary.

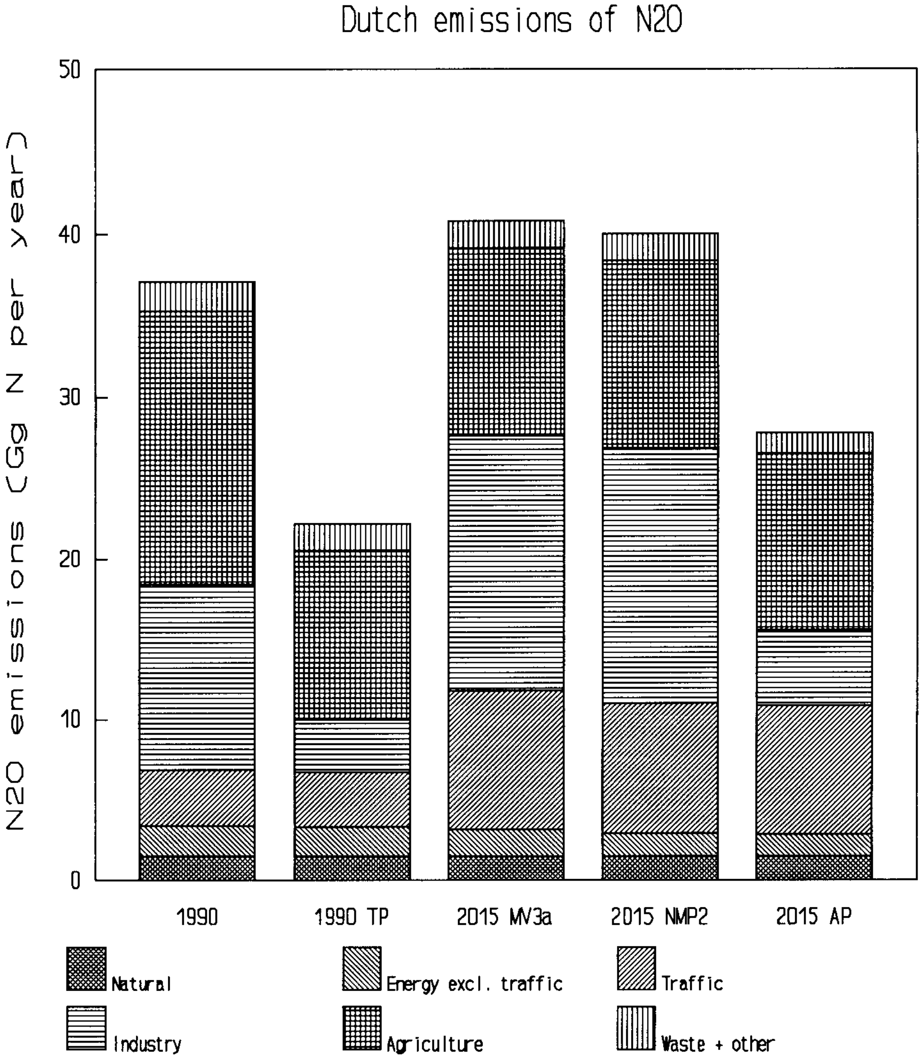

Fig. 7-1. Dutch 1990 emissions of N_2O (1990), the 1990 emissions minus the theoretical technical potential to reduce emissions (TP) (if nothing else would change), and the 2015 projections based on current policy (MV3a), the National Environmental Policy Plan (NMP2) and additional policy (AP).

7.2 Recommendations

7.2.1 Measures to reduce Dutch emissions of N_2O

Although important uncertainties exist, it is likely that without additional policy Dutch emissions will continue to increase (Fig. 7-1). Additional policy measures could, by 2000, reduce Dutch emissions of N_2O by almost 11 Gg N y^{-1}, relative to the NMP-2 projections. By 2015 the emissions could be 12 Gg N y^{-1} lower (see also Table 6-13). Most of the technological options involved need further investigation, and also the costs of options should be investigated. This leads to the recommendations listed in the following.

1. Industry. The most effective additional policy option to reduce N_2O emissions may be reduction of N_2O emissions in nitric acid production by a catalytic converter. Optimization of the production process may add to the reduction. Dutch annual N_2O emissions are calculated to be reduced by 9.7 Gg N in 2000, and by 11.2 Gg N in 2015 by these options. This is about 90% of the total reduction as achieved in the additional policy scenario. Assuming full implementation of such a catalytic converter by the year 2000 is highly optimistic, but not impossible.
   A catalytic converter for N_2O reduction in nitric acid production is presently not available. Similar converters are used in adipic acid production. However, these perform at relatively high temperatures, which, in nitric acid production, would require additional energy input. It is therefore desirable to develop a new catalytic converter, which performs at lower temperatures. This is probably possible within a few years. Before practical implementation of the new catalytic converter, the costs and side-effects on, for instance, NOx and NH_3 emission need to be investigated. Implementation itself may take a long time, however, the process of implementation could proceed faster if N_2O is included and given priority in industrial environmental plans (so-called "Bedrijfs Milieu Plannen") in negotiation with the industry. It is possible to include N_2O emissions in the environmental permits for Dutch industries, or in the specific Dutch General Administrative Order ("Algemene Maatregel van Bestuur") for nitric acid production.
   Summarizing, N_2O emissions from nitric acid production can be reduced considerably if (i) development of a suitable catalytic converter is promoted and (ii) implementation of this catalyst is given priority.

2. Agriculture. Emissions of N_2O from Dutch agriculture can be reduced considerably by implementation of existing policy and the NMP-2. Additional options could further reduce annual N_2O emissions by 0.5 - 0.6 Gg N from 2000 on. Recommendable options include:
   - A stop and reverse of dessication by restoring the groundwater level in both natural terrains and agricultural soils, in particular in organic soils.
   - Improved fertilizer efficiency. This could be achieved through (i) increased use of slow-release fertilizers, which is a relatively effective option, and (ii) more effective use of animal manure as fertilizer, resulting in a reduction in

synthetic fertilizer use. These options reduce both N_2O emissions from soils and leaching.
- No technical options are available to reduce manure-induced emissions of N_2O. This study shows that future emissions can be effectively avoided by not implementing deep-litter stables and HNO_3 treatment of manure (both measures to reduce NH_3 emissions). The only practical way to actually reduce manure-induced emissions would be a reduction in manure-N production.

3. Waste. The additional policy options for waste could reduce annual N_2O emissions by about 0.3 Gg N from 2000. These options include:
   - Optimized combustion of municipal solid waste, which may reduce N_2O production during incineration. A shift to temperature > 950 °C for a few seconds is probably sufficient to reduce most of the N_2O formed. This could be included in regulations.
   - Optimized sewage treatment, which requires further research. In addition, a reduction in the N content of wastewater would reduce N_2O emissions.

4. Energy: stationary combustion. The technical options available for stationary combustion in the energy sector have a potential to reduce annual emissions from 2000 by about 0.1 Gg N. Emissions would be effected more by increased energy efficiency or the use of non-fossil sources. To reduce N_2O emissions the following technical options could be considered:
   - Improvement of stationary combustion processes. In stationary combustion N_2O emissions could be reduced by improvement of the combustion process. It is common practice in Dutch electricity generation to strive for high efficiency, so that this option is probably only effective in older power plants. It would be new if power plants would optimize for N_2O emissions as well. This option requires some research.
   - Avoiding selective non catalytic reduction (SNCR). If a NOx reduction step is required, selective catalytic reduction (SCR) is to be preferred if N_2O emissions are to be kept low. If SNCR is used, use of NH_3 gives lower N_2O emissions than use of ureum or cyanuric acid.
   - Afterburning, or a catalytic reduction step in fluidized bed combustion (FBC). This is a demonstrated technology which could be relatively easily implemented. There is, however, not much FBC in the Netherlands so that this option has a limited effect.

5. Energy: mobile combustion. There are at present few technologies available to reduce N_2O emissions from transport. It is not likely that a catalyst which does not increase N_2O emissions and has equal performance for NOx, VOC and CO as the current 3-way catalyst will soon become available in mobile combustion. It seems therefore recommendable to concentrate on other options to reduce N_2O emissions from traffic:
   - Development of low-NOx engines. Development of a low-NOx engine, not

requiring a catalyst, seems a promising option to avoid N_2O emissions. In general, all vehicles that do not need a 3-way catalyst emit less N_2O than 3-way catalyst-equipped vehicles.

- Promotion of electric modes of transportation. Both trains and electric cars emit less N_2O than other road vehicles. The potential of these options is not quantified, but could be considerable.
- Including N_2O in the list of so-called "registered" compounds. This would not only provide new data about the actual source strength, but also give opportunities for regulation. It would give more insight in the process of catalyst aging; if it proceeds slowly enough, early replacement could be considered as an option to reduce N_2O emissions.
- Reduce urban driving and traffic jams. Vehicles tend to emit relatively large amounts of N_2O when driving in cities and in traffic jams. An overall reduction in automobility would also reduce N_2O emissions.

7.2.2 Reducing the uncertainties

Method II results in a more complete inventory of N_2O emissions than method I. Therefore it is recommended here to use method II for making national emission inventories. Nevertheless, there are still some gaps in the knowledge about N_2O. Additional research could reduce the uncertainties. Additional research is recommended for the following relatively large sources of N_2O:

1. Industrial sources. Nitric acid production is an important source in the Netherlands, and may be the most effective option for reduction. It is therefore important to reliably estimate the source strength. However, only a few measurements of N_2O emissions have been published, and these are all from abroad. It is not always clear during which process the observed N_2O was formed. Moreover, the observations only involve nitric acid and adipic acid production, while it is likely that more industrial sources exist. A deskstudy on this could result in an first inventory of potential sources of N_2O in Dutch industry. In addition, actual measurements in both nitric acid production and other industries are desirable for making more reliable estimates of Dutch emissions.

2. Traffic. The present inventory indicates that traffic is a relatively important source of N_2O in the Netherlands. As a result of the introduction of 3-way catalysts, emissions are expected to increase relatively fast within the coming decade. The amount of N_2O produced in vehicles depends on many factors. More measurements of N_2O concentrations in vehicle exhaust gases would narrow the uncertainties. The emission factor uses in method II are based on measures N_2O concentrations in vehicle exhaust during test driving cycles. Extrapolation of these laboratory observations to the actual situation is difficult. To reduce the uncertainties, it is recommendable to further investigate N_2O production in traffic; especially emissions from vehicles having (aged) 3-way catalysts and heavy duty diesel

trucks, because these are relatively large sources of N_2O. In addition to the usual laboratory measurements, the actual source could be estimated more reliably after measuring N_2O in tunnels.

3. Soil emissions. The results of recent measurement campaigns in the Netherlands are used in developing method II. The measurements were performed on grasslands only. Continuation of this monitoring, and extension to other soil types, farming systems, or stables would further improve the method.

4. Groundwater and surface waters. A considerable amount of nitrogen leaches from soils, and may lead to N_2O production in groundwater and surface waters. In addition, there are nitrogen inputs to surface waters from other sources, such as industries, sewage treatment plants and atmospheric deposition. The associated N_2O emissions are highly uncertain.

Two minor potential sources of N_2O are relatively poorly known:

5. Atmospheric formation of N_2O is a poorly known source. It has been calculated, however, that it is a minor source of N_2O in the Netherlands.

6. Global warming. When the temperature of the earth increases N_2O emissions may increase simultaneously. Since the temperature in the Netherlands has not been anthropogenically increased (yet) Dutch N_2O emissions are not (yet) enhanced. However, this may change in the future. The extent to which emissions could increase has never been investigated for the Netherlands.

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Appendix 1-1. List of abbreviations and definitions

Abiogenic emissions	emissions not caused by boplogical processes.
Anthropogenic emissions	emissions as a result of human activities.
Background emissions	emissions that are not induced by anthropogenic nitrogen fluxes such as fertilizer, manure, biological nitrogen fixation, or atmospheric deposition; the anthropogenic backgound emission is the differece between current background emission and the historic natural emission. Current background emissions are enhanced as a result of human activities.
Biogenic emissions	emissions resulting from biological processes.
FBC	Fluidized Bed Combustion.
FCCC	Framework Convention on Climate Change.
GWP	Global Warming Potential, defined by IPCC as the time-integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg of carbon dioxide (Houghton et al., 1990).
IPCC	Intergovernmental Panel on Climate Change.
MSW	Municipal Solid Waste
MV3	National Environmental Outlook 3 (RIVM, 1993a).
MV3a	updat of National Environmental Outlook 3 (RIVM, 1993b).
N	nitrogen.
Natural emissions	emissions that are not induced or enhanced by human activities; *natural biogenic emissions* are defined as biogenic emissions from the natural terrestrial and aquatic ecosystems in the pre-agricultural era; *natural abiogenic emissions* result from abiogenic formation of N_2O in the unpolluted atmosphere.
NMP 2	Dutch National Environmental Policy Plan 2.

ODP	Ozone Depleting Potential.
Pre-industrial era	period before human activities influenced atmospheric N_2O significantly, i.e. before the year 1900.
SCR	Selective Catalytic Reduction.
SNCR	Selective Non Catalytic Reduction.

Appendix 4-1. IPCC emission factors

Table A-1. Method I emission factors for mobile sources (Olivier, 1993b). Third column: to be used in inventories.

Vehicle type	Emission factors g N_2O per km*	Emission factors g N_2O GJ^{-1}**	Uncertainty range g N_2O per km
Passenger uncontrolled:			
gasoline car	NA/0.005	NA/0.9	0.004-0.06
gasoline car, 2-stroke engine	NA	NA	NA
diesel car	NA/0.014	NA/1.9	0.02-0.06
LPG car	NA	NA	NA
Natural gas (CNG) car	NA	NA	NA
motor cycle	NA/0.002	NA/0.9	NA
biofuel car (ethanol, methanol)	NA	NA	NA
Passenger, controlled:			
non-catalytic controlled gasoline car	NA/0.005	NA/0.9	NA
oxidation catalyst, gasoline car	NA/0.027	NA/4.9	NA
early 3-way catalyst gasoline car	NA/0.046	NA/13.0	NA
advanced „	NA/0.019	NA/6.9	NA
aged catalyst gasoline car	NA	NA	0.05-0.32
moderate controlled diesel car	NA/0.010	NA/1.9	NA
advanced controlled diesel car	NA/0.007	NA/1.9	NA
catalyst equipped LPG car	NA	NA	NA
catalyst equipped methanol car	NA	NA	NA/0.002-0.004***
non-catalyst controlled motor cycle	NA/0.002	NA/0.9	NA
Freight, uncontrolled:			
low-duty gasoline vehicle	NA/0.006	NA/0.9	0.004-0.06
low-duty diesel vehicle	NA/0.017	NA/1.9	0.02-0.06
low-duty LPG vehicle	NA	NA	NA
low-duty CNG vehicle	NA	NA	NA
heavy-duty gasoline vehicle	NA/0.009	NA/0.5	NA
heavy-duty diesel vehicle	NA/0.031	NA/1.9	NA
heavy-duty LPG vehicle	NA	NA	NA
heavy-duty CNG vehicle	NA	NA	NA
Freight, controlled:			
Non-catalyst LD gasoline truck	NA/0.006	NA/0.9	NA
Oxidation catalyst LD gasoline truck	NA/0.031	NA/4.8	0.03-0.084
Early 3-way catalyst gasoline truck	NA/0.063	NA/13.0	NA
advanced 3-way catalyst LD gasoline truck	NA/0.024	NA/6.8	NA
moderate controlled LD diesel truck	NA/0.014	NA/1.9	NA
advanced controlled LD diesel truck	NA/0.009	NA/1.9	NA
catalyst equipped LD LPG truck	NA	NA	NA
non-catalyst controlled HD gasoline truck	NA/0.006	NA/0.5	NA
oxidation catalyst HD gasoline truck	NA	NA	NA
3-way catalyst HD gasoline truck	NA/0.006	NA/0.5	NA
moderate controlled HD diesel truck	NA/0.025	NA/1.9	NA
advanced controlled HD diesel truck	NA/0.025	NA/1.9	NA

NA = Not Available; NA/... = Not Available/USA data; * preliminary estimate for US vehicles; ** assumed fuel economy: 12 km/l gasoline; 15 km/l diesel; *** preliminary estimate for Japanese vehicles.

Table A-2. Method I emission factors for stationary combustion (Olivier, 1993b).

Technology	Emission factors g N_2O GJ^{-1} energy input or g N_2O per ton waste	Uncertainty range (ibidem)
Conventional facilities, uncontrolled:		
Coal	1.4	0-10
Oil	0.6	0-2.8
Gas	0.1	0-1.1
Conventional facilities, controlled:		
Selective Catalytic Combustion (NOx Reduction? SCR?)	see uncontrolled	see uncontrolled
Non Selective Catalytic NO Reduction (NSCR)	NA	10-100***
Other combustion facilities:		
Fluidized Bed Combustion - hard coal**	NA	10-95**
Fluidized Bed Combustion (FBC) - brown coal, peat wood**	NA	10-30**
Gas turbines - oil, gas	NA	0-5*
Waste incineration:		
Municipal waste combustion	30 (g per ton)*	10-200 (g per ton)*
sludge incineration	630 (g per ton)*	100-1000 (g per ton)*
Non-commercial fuels:		
Fuelwood	NA	NA
Charcoal****	NA	NA
Crop residues/dung	NA	NA

NA = Not Available; * preliminary estimate; ** if the combustion temperature exceeds 1000 °C one may use a range of 0-10; *** preliminary estimate with NH_3 injection at lower end and with urea injection at higher end of range; **** production, combustion (residential, commercial) use in steel manufacturing

Table A-3. Method I emission factors for non-road transport (Olivier, 1993b).

Activity	Emission factor (g N_2O GJ^{-1})	Uncertainty range (g N_2O kg^{-1})
Sea ships (diesel)	2*	NA
Ships (int.nav.)(diesel)	2	NA
Locomotives (diesel)	2	NA
Off-road vehicles** (diesel)	2	NA
Aircraft (jet fuel)	NA	NA
Aircraft (aviation gasoline)	0.9*	NA

NA = Not Available; * preliminary estimate (assumed to be similar to heavy duty diesel vehicles and uncontrolled gasoline passenger cars; ** e.g. farm and construction equipment.

Appendix 4-2. A comparison between "method II", *National Environmental Outlook 3* (MV3), and the Dutch "Emissie Jaarrapport"

In this appendix method II is compared to the methodology used in the Dutch *National Environmental Outlook 3*, hereafter referred to as MV3 (RIVM, 1993a; Van Amstel et al., 1994). The MV3 methodology was used for the National Communication of the Netherlands for the Climate Convention (VROM, 1994, Van Amstel et al., 1994). The inventories recently reported in the Dutch "Emissie Jaarrapport (EJR)" equal, with some exceptions, those in MV3 (Berdowski et al., 1994). Berdowski et al. (1994) explain the differences between EJR and MV3.

Table A-4 shows that method II results in somehwat lower N_2O emissions for 1990 than MV3, although method II includes more sources. The differences between the two methods are listed below. EJR is only mentioned when it report different emissions than MV3.

1. Natural emissions

In MV3 natural background emissions from both agricultural and natural terrain are included in agricultural emissions, and may be less than 2 Gg N y^{-1} (Van Amstel et al., 1993). Natural emissions from surface waters and atmospheric formation are not taken into account in MV3 and method II.

In EJR an alternative definition of "nature" is used: it includes all terrains that are not agricultural, so that the anthropogenically induced emissions from surface waters are included in this category. EJR does not take into account non-anthropogenic (= natural in MV3) emissions.

2. Energy

There is no difference between method II and MV3 in the methodology for emissions from stationary and mobile combustion. The difference in the 1990 emissions for stationary combustion is a result of revised activity levels (energy use).

EJR is different for stationary combustion, for which emissions from the Dutch Emission Registration are used (VROM, 1993), in which N_2O emissions from stationary combustion are 0.

3. Industry

Method II and MV3 use similar emission factors, but the activity data differ for industrial emissions. EJR includes only emissions from the Dutch Emission Registration (VROM, 1993), so that nitric oxide is not included in EJR.

4. Agriculture

- *Background emissions from agricultural soils.* In MV3 agricultural emissions are calculated using the "country" approach of Bouwman and Van der Hoek (1991). This approach is adopted in method II for the calculations of total background emissions. However, for grassland on organic soils the total background emission is set at 10 instead of 27.5 kg N ha^{-1} y^{-1}, based on recent research in the Netherlands, and the background emissions for mineral soils is set a 1.0 kg N ha^{-1} y^{-1}, based on Bouwman (1994).
- *Fertilizers.* The N_2O emissions from synthetic fertilizer input and manure are in method II calculated using 4 emission factor classes, while the "country" approach used in MV3 assumes one emission factor for synthetic fertilizers (0.4% of N input) and one for animal waste (0.7% of N input).
- *Atmospheric deposition of NH_3.* In method II this is considered a seperate source of N_2O, while in MV3 it is included in animal waste. Both methods calculate the related N_2O emissions as a % of the NH_3-N emissions.
- *Stables.* Emissions from stables and storage of manure are included in method II, but not in MV3.
- *Legumes.* In MV3 N_2O emissions from legumes are calculated as 3 kg N ha^{-1} y^{-1}, while method II uses emission factor class 2.
- *Leaching.* In MV3 these emissions are calculated as 2.7% (2 - 3.9)% of the nitrogen input into Dutch waters is emited as N_2O, which was considered this an upper limit. In method II class 2 emission factors are used (0.2 - 1.25%).
- *Other manure.* In MV3 a category "other manure" is considered, including manure of for instance cats and dogs. This source is not taken into account in method II.
- *EJR.* In EJR the MV3 method is adopted, except for leaching. EJR does not consider emissions from coastal waters, and includes emissions from inland waters (induced by N leaching and other N inputs) in the category "Nature".

5. Waste

- *MSW incineration.* There is no difference between method II and MV3 for incineration of Municipal Solid Waste. EJR adopts emissions from the Dutch Emission Registration (VROM, 1993), in which N_2O emissions from waste incineration are 0.
- *Sewage treatment plants.* Method II uses a lower emission facor (0.2 - 1.25% of N-removel) for sewage treatment than MV3 (5 - 10%), based on recent measurements in Dutch plants (BKH, 1994).

6. Other

"Other nitrogen loading to surface waters" is included in MV3, but the method used is different (see leaching from agriculture). MV3 does not include atmospheric formation, atmospheric deposition of NOx or non-agricultural NH_3, and anaesthesia.

Table A-4. Dutch 1990 emissions of N_2O according to method II (this report) and *National Environmental Outlook 3* (MV3) (RIVM, 1993a; Van Amstel et al., 1994); NE = Not Estimated

Source	MV3	Method II	Difference (II-MV3)
Natural emissions			
- soils	included in agriculture	1.5	?
- atmospheric formation	NE	<0.1	<0.1
- surface waters	NE	NE	
Energy			
- stationary combustion	0.4	0.7	0.2
- mobile combustion	3.4	3.4	0.0
- atm. deposition of NOx	NE	1.2	1.2
Industry			
- adipic acid	0.0	0.0	0.0
- nitric acid	9.4	10.5	1.1
- other	1.1	1.1	0.0
Agriculture			
- background	10.6[1]	3.0	-7.6
- synthetic fertilizer	1.7	4.4	2.7
- animal manure (soil emission)	3.6[2]	7.0[3]	3.5
= atm. deposition of NH_3			
- stables	NE	0.5	0.5
- legumes	0.1	0.2	0.1
- leaching	4.9	1.8	-3.1
Waste			
- MSW incineration	<0.1	<0.1	0.0
- Sewage treatment plants	2.6	0.3	-2.3
Other			
- atmospheric formation	NE	<0.1	<0.1
- other N-loading surface waters	2.0	0.6	-1.4
- atm. deposition non-agric. NH_3	NE	0.1	0.1
- atm. deposition non-energy NOx	NE	0.5	0.5
- anaesthesia	NE	0.3	0.3
Total	39.8	37.1	-2.7

[1] including natural emissions; [2] including NH_3 deposition on agricultural soils and natural terrain; [3] manure used as fertilizer + N excretion in meadows.

Appendix 6-1. Activity data and N_2O emissions for stationary combustion

Table A-5. Energy use in the Netherlands (PJ y^{-1}), excluding transport, and related N_2O emissions (Gg N_2O-N y^{-1}) for the period 1980 - 1992, and for 2000 - 2015 in the current policy projections (MV3a)

Sector	Emission factor[2]	1980	1985	1990	1991	1992	2000 MV3a	2010 MV3a	2015 MV3a
Energy use[1]									
Gas	0.064	1255	1332	1414	1464	1495	1658	1755	1586
Oil	0.382	866	525	591	602	599	568	690	726
Coal; non FBC	0.981	164	264	366	336	334	306	406	556
Coal; FBC	26.7	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
other	0	102	78	91	89	99	172	117	141
Total		2389	2201	2464	2493	2529	2706	2970	3011
N_2O emissions									
Gas		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Oil		0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Coal; non FBC		0.1	0.2	0.3	0.3	0.3	0.3	0.4	0.5
Coal; FBC		<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
other		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total		0.6	0.6	0.7	0.7	0.7	0.6	0.8	0.9

[1] Including feedstock; excluding bunkers, temperature corrected (Van Amstel et al., 1994; Albers et al., 1993); [2] Method II emission factors in g N_2O-N GJ^{-1}, Table 4-12.

Table A-6 Energy use in the Netherlands (PJ y^{-1}), excluding transport, and related N_2O emissions (Gg N_2O-N y^{-1}) for the period 2000 - 2015 in the NMP-2 (National Environmental Policy Plan 2) and AP (Additional Policy) projections

Sector	Emission factors[2]	2000 NMP-2	2010 NMP-2	2015 NMP-2	2000 AP[3]	2010 AP[3]	2015 AP[3]
Energy use[1]							
Gas	0.064	1529	1700	1531	1529	1700	1531
Oil	0.382	568	690	726	568	690	726
Coal; non-FBC	0.981	283	396	546	283	396	546
Coal; FBC	26.7	1.6	1.6	1.6	1.6	1.6	1.6
other	0	172	117	141	172	117	141
Total		2554	2905	2946	2554	2905	2946
N_2O emissions							
Gas		0.1	0.1	0.1	0.1	0.1	0.1
Oil		0.2	0.2	0.3	0.2	0.2	0.3
Coal; non-FBC		0.3	0.3	0.5	0.2	0.2	0.4
Coal; FBC		<0.1	<0.1	<0.1	<<0.1	<<0.1	<<0.1
other		0.0	0.0	0.0	0.0	0.0	0.0
Total		0.6	0.6	0.9	0.5	0.5	0.8

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[1] Including feedstock; excluding bunkers, temperature corrected (Van Amstel et al., 1994; Albers et al., 1993); [2] Method II emission factors, see Table 4-12; [3] Reduction options a.1 (improved combustion), a.3 (afterburning in FBC) and a.4 (catalytic reduction in FBC), Table 5.7

Appendix 6-2. Activity data and N_2O emissions for transport

Table A-7. Vehicle-kilometers driven in the Netherlands (millions per year) and related N_2O emissions (Gg N y^{-1}) for the period 1980 - 1992

	1980	1985	1990	1991[1]	1992[1]
Vehicle-kilometers[2]					
Passenger cars					
- gasoline	49450	46516	50519	51246	54310
- diesel	4197	9462	15293	15543	15350
- LPG	7705	11854	14233	14030	13680
Freight vehicles					
- low duty gasoline	2069	1728	1698	1635	1630
- low duty diesel	1541	2641	5551	6033	6538
- low duty LPG	337	378	440	422	430
- heavy duty trucks	3497	3228	3700	3641	3946
- heavy duty trailers	1405	1654	2304	2359	2556
Special vehicles					
- gasoline	57	96	48	38	30
- diesel	440	308	307	293	290
Buses (diesel)	560	590	628	624	630
Motorcycles	878	702	946	1017	1080
Mopeds	1920	1710	1710	1310	1190
Water/rail etc.[3]	1517	1517	1517	1512	1512
N_2O emission[4]					
Passenger cars					
- gasoline	0.5	0.4	1.1	1.1	1.2
- diesel	0.1	0.2	0.3	0.3	0.3
- LPG	0.1	0.1	0.3	0.3	0.3
Freight vehicles					
- low duty gasoline	<0.1	<0.1	<0.1	<0.1	<0.1
- low duty diesel[5]	<0.1	0.1	0.1	0.1	0.1
- low duty LPG	<0.1	<0.1	<0.1	<0.1	<0.1
- heavy duty trucks[5]	0.4	0.4	0.5	0.5	0.5
- heavy duty trailers[5]	0.2	0.2	0.3	0.3	0.3
Special vehicles					
- gasoline	<0.1	<0.1	<0.1	<0.1	<0.1
- diesel	<0.1	<0.1	<0.1	<0.1	<0.1
Buses (diesel)	0.1	0.1	0.1	0.1	0.1
Motorcycles	<0.1	<0.1	<0.1	<0.1	<0.1
Mopeds	<0.1	<0.1	<0.1	<0.1	<0.1
Water/rail etc.	0.7	0.7	0.7	0.7	0.7
Total	2.1	2.2	3.4	3.4	3.6

[1] 1991/92 tentative; [2] 1980-90 data from CBS, 1992; 1991 from Thomas, pers.comm.; 1992 from CBS, 1993; [3] Gg fuel; 1980/85 assumed to be as 1990; 1992 assumed to be as 1991; [4] Using method II emission factors (Table A-9); [5] 1992 Ratio vehicle-km diesel:heavy duty as in 1991.

Table A-8. Future vehicle-kilometers driven in the Netherlands (millions per year) and related N_2O emissions (Gg N_2O-N y^{-1}) for the period 2000 - 2015

	Current policy (MV3a)[1]			NMP-2/AP[1]		
	2000	2010	2015	2000	2010	2015
Vehicle-kilometers[1]						
Passenger cars						
- gasoline	50211	53816	55118	47949	48523	49910
- diesel	23725	26752	28764	22656	24121	26046
- LPG	14914	17087	17775	14242	15406	16096
Freight vehicles						
- low duty gasoline	2123	2836	3192	2123	2836	3192
- low duty diesel	6939	9270	10436	6939	9270	10436
- low duty LPG	550	735	827	550	735	827
- heavy duty trucks	4921	7104	8325	4291	7104	8325
- heavy duty trailers	2742	3871	4562	2742	3871	4562
Special vehicles						
- gasoline	54	60	62	54	60	62
- diesel	344	381	399	344	381	399
Buses (diesel)	798	697	697	789	713	716
Motorcycles	1419	1419	1419	1419	1419	1419
Mopeds	1710	1710	1710	1710	1710	1710
Water/rail etc.[2]	1545	1551	1480	1545	1551	1480
N_2O emission[3]						
Passenger cars						
- gasoline	3.4	3.7	3.8	3.3	3.3	3.4
- diesel	0.5	0.5	0.6	0.4	0.5	0.5
- LPG	1.0	1.2	1.2	1.0	1.1	1.1
Freight vehicles						
- low duty gasoline	0.2	0.3	0.3	0.2	0.3	0.3
- low duty diesel[5]	0.1	0.2	0.2	0.1	0.2	0.2
- low duty LPG	<0.1	0.1	0.1	<0.1	0.1	0.1
- heavy duty trucks[5]	0.6	0.9	1.1	0.6	0.9	1.1
- heavy duty trailers[5]	0.3	0.5	0.6	0.3	0.5	0.6
Special vehicles						
- gasoline	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
- diesel	<0.1	<0.1	0.1	<0.1	<0.1	0.1
Buses (diesel)	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Mopeds	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Water/rail etc.	0.7	0.7	0.6	0.7	0.7	0.6
Total	7.1	8.1	8.6	6.9	7.6	8.0

[1] European Renaissance scenario (RIVM, 1993a; Van Amstel et al., 1994); MV3a = current policy (RIVM, 1993b), NMP-2 = National Environmental Policy Plan 2 (RIVM, 1993b); AP = Additional Policy; [2] kg fuel; [3] method II emission factors (Table A-9)

Table A-9. Method II emission factors[1] for transport (g N_2O km^{-1}, for g N km^{-1} multiplied by 28/44)

	1980-1985[2]	1990-1992[3]	2000-2015[4]
Passenger cars			
- gasoline	0.015	0.034	0.107
- diesel	0.031	0.031	0.031
- LPG	0.015	0.034	0.107
Freight vehicles			
- low duty gasoline	0.015	0.045	0.142
- low duty diesel	0.031	0.031	0.031
- low duty LPG	0.015	0.045	0.142
- heavy duty trucks	0.200	0.200	0.200
- heavy duty trailers	0.200	0.200	0.200
Special vehicles			
- gasoline	0.015	0.045	0.142
- diesel	0.200	0.200	0.200
Buses (diesel)	0.200	0.200	0.200
Motorcycles	0.010	0.010	0.010
Mopeds	0.004	0.004	0.004
Water/rail etc.[5]	0.690	0.690	0.690

[1] emission factors from Baas (1991) (Table 4-12); emission factors for gasoline/LPG vehicles increase as a result of introduction and aging of 3-way catalysts; [2] no catalytic converter equipped vehicles; [3] vehicle-kilometers by gasoline/LPG vehicles: 65% no catalyst, 13% oxidation catalyst, 7% new 3-way catalysts, 15% old catalyst (Baas, 1991); [3] 15% and 85% of gasoline/LPG vehicle-kms with new and old 3-way catalyst, respectively; [5] g N_2O-N per kg fuel; based on emission factor for heavy duty diesel trucks.

Appendix 6-3. Activity data and N_2O emissions for industry

Table A-10. Nitric Acid production in the Netherlands (Gg HNO_3-N y^{-1}), related N_2O emissions (Gg N y^{-1}) and N_2O emissions from other chemical industries (Gg N y^{-1}) for the period 1980 - 1992 and for 2000 - 2015 MV3a (current policy), NMP-2 (National Environmental Policy Plan 2, and AP (Additional Policy) projections

	1980	1985	1990	1991	1992	2000	2010	2015
Nitric Acid production[1]	440	545	617	617	617	710	790	821
						MV3a/ NMP-2	MV3a/ NMP-2	MV3a/ NMP-2
N_2O emission nitric acid[2]	7.5	9.3	10.5	10.5	10.5	12.1	13.4	14.0
Other industrial N_2O[3]	1.1	1.1	1.1	1.1	1.1	1.4	1.8	1.9
Total	8.6	10.4	11.6	11.6	11.6	13.5	15.2	15.9
						AP	AP	AP
N_2O emission nitric acid[4]						2.4	2.7	2.8
Other industrial N_2O						1.4	1.8	1.9
Total						3.8	4.4	4.7

[1] Used in MV3a, NMP-2 and AP; 1980 and 1985: Olivier (pers.comm.), Van Amstel et al. (1994); 1990: Dutch Emission Registration (VROM, 1993; Hoogenkamp, pers.comm.); 1991 and 1992 set equal to 1990; 2000 - 2015: increase based on growth in synthetic fertilizer production (15%, 28% and 33% increase in 2000, 2010 and 2015, respectively, relative to 1990); [2] Method II emission factor: 0.017 g N_2O-N per kg HNO_3-N, see Table 4-12; [3] 1990 emission from the Dutch Emission Registration (VROM, 1993), other 1980-1985 and 1991-1992 assumed to be equal to 1990, for future growth rates as in petrochemical industry (31%, 63% and 78% increase in 2000, 2010 and 2015, respectively, relative to 1990); Olivier (1993b); [4] Reduction options e.1 (catalytic N_2O reduction) and e.2 (improved production process), see Table 5-7.

Appendix 6-4. Activity data for agriculture

Table A-11. Agricultural areas (hectare) in the Netherlands[1] as used in the MV3 (pre-current policy), MV3a (current policy), NMP-2 (National Environmental Policy Plan 2) and AP (additional policy) projections

	1980	1985	1990	1991	1992	2000	2010	2015
Grassland total	1197592	1164290	1096496	1079857	1063609	989100	956130	945140
Grassland organic	299398	291073	274124	269965	265902	247275	239033	236285
Grassland mineral	898194	873218	822372	809893	797707	741825	717098	708855
Arable total	822644	854733	909113	910999	921904	946620	891720	868070
Legumes	10400	28400	32300	27000	23400	23666	22293	21702
Arable (excl. legumes)[2]	812244	826333	876813	883999	898504	922955	869427	846368

[1] Van Amstel et al. (1994); [2] including fallow land and horticulture.

Table A-12. N-excretion by Dutch livestock, synthetic fertilizer use, and NH_3-N emissions for the period 1980 - 1992 and projections for 2000 - 2015 as used in MV3 (pre-current policy, not including "derde fase mestbeleid"); from Van der Hoek (1994, and pers.comm.)

	1980	1986	1990	1991	1992	2000 MV3	2010 MV3	2015 MV3
Animal manure incl. NH_3 (Gg N y^{-1})								as 2010
total N excretion	622	650	585	639	619	470	459	
- produced in meadow	176	169	148	160	148	122	120	
- produced in stable	445	481	438	479	471	348	339	
available as fertilizer	378	410	371	406	398	303	309	
- veal calf manure	0	0	5	6	6	5	5	
- export	0	0	6	7	11	65	70	
used on Dutch soil	378	410	359	393	381	234	235	
synthetic fertilizer use incl. NH_3 (Gg N y^{-1})								
Total	483	500	412	400	392	177	145	
NH_3-N emission (Gg N y^{-1})								as 2010
contribution manure	184.5	189.6	155.6	160.8	120.1	62.2	47.0	
- from meadow	25.5	13.4	12.2	13.7	11.9	9.6	9.2	
- from stable/storage	67.5	70.7	67.1	73.4	72.9	45.0	30.1	
- from application	91.4	105.4	76.3	73.7	35.3	7.5	7.7	
from synthetic fertilizer use	8.2	9.9	8.7	8.5	7.7	3.3	3.3	
from industry	6.6	5.8	4.2	3.7	3.7	2.5	2.5	
from households	7.4	7.4	8.6	8.6	8.7	9.1	9.1	
total NH_3-N emission	206.7	212.7	177.1	181.6	140.3	77.0	61.9	

Table A-13. N excretion by Dutch livestock and NH_3-N emissions for the period 1980 - 1992 and projections for 2000 - 2015 as used in MV3a (current policy, including "derde fase mestbeleid"), NMP-2 (National Environmental Policy Plan 2, including "derde fase mestbeleid" and AP (additional policy); from Van der Hoek (1994, and pers.comm.)

	2000 MV3a/NMP-2	2010 MV3/NMP-2	2015 MV3/NMP-2	2000 AP[1]	2010 AP[1]	2015 AP[1]
animal manure incl. NH_3 (Gg N y^{-1})						
total N-excretion	444	413	as 2010	444	413	as 2010
- produced in meadow	115	109		115	109	
- produced in stable	329	304		329	304	
available as fertilizer	288	276		288	276	
- veal calf manure	5	5		5	5	
- export	113	102		113	102	
used on Dutch soil	170	169		170	169	
synthetic fertilizer use incl. NH_3 (Gg N y^{-1})						
total	208	178		187	160	
NH_3-N emission (Gg N y^{-1})[7]						
contribution manure	56.1	42.7	as 2010	56.1	42.7	as 2010
- from meadow	9.0	8.3		9.0	8.3	
- from stable/storage	41.1	28.5		41.1	28.5	
- from appl. manure	5.9	5.9		5.9	5.9	
from synthetic fertilizer use	3.3	3.3		3.0	3.0	
from industry	2.5	2.5		2.5	2.5	
from households	9.1	9.1		9.1	9.1	
total NH_3-N emission	70.9	57.5		70.9	57.5	

[1] A reduction of synthetic fertilizer use by 10% relative to the NMP-2 projections (reduction options h.3 - h.7; Table 5-7)

Table A-14. Assumed percent of manure applied to soil by injection, sod injection ("zodeinjectie"), sod manuring ("zodebemesting") and working it in through 1 or 2 activities ("onderwerken in 1 of 2 bouwgangen"), and assumed ratio urine-N : faeces-N for N excreted in meadows (van der Hoek, pers.comm.) used in the MV3, MV3a, NMP-2, and AP projections

Year	Manure applied to soils by injection etc. (% of N applied)[1]	urine-N : faeces-N when excreted in meadow
1980	0	70 : 30
1985	0	70 : 30
1990	0	60 : 40
1991	grassland 12, arable 5	60 : 40
1992	grassland 33, arable 100	60 : 40
2000	100	50 : 50
2010	100	50 : 50
2015	100	50 : 50

[1] assuming that all cattle manure is applied to grassland; and all other animal manure to arable land

Table A-15. Activity data (in Gg N y^{-1} unless mentioned otherwise) and emission factors (as fraction of N flux unless mentioned otherwise) for agriculture for 1980 - 1992, and MV3 projections (not including the Dutch "derde fase mestbeleid") for 2000 - 2015

	Emission factor[14]	1980	1985	1990	1991	1992	2000 MV3	2010 MV3	2015 MV3
Background emissions									
Natural	1.5								
Anthropogenic									
- grassland on organic soil	10.0	as 1990	as 1990	274124 ha	as 1990	as 1990	as 1990	as 1990	as 1990
- grassland on mineral soil + arable	1.0	as 1990	as 1990	1731485 ha	as 1990	as 1990	as 1990	as 1990	as 1990
Synthetic fertilizer use excl. NH_3									
- on mineral soil[1]	0.010	427	441	363	352	346	156	128	
- on organic soil[1]	0.020	47	49	40	39	38	17	14	
Total[2]		475	490	403	392	384	174	142	as 2010
Manure excl. NH_3									
Meadow		151	156	136	146	136	112	110	
- urine in meadow[3]	0.020	105	109	82	88	82	56	55	
- faeces in meadow[3]	0.010	45	47	54	59	54	56	55	
Stable/storage		378	410	371	406	398	303	309	
- deep litter stable[4]	0.050	0	0	0	0	0	0	0	
- aerobic storage[5]	0.050	0	0	0	0	0	0	0	
- biologically treated[6]	0.020	0	0	5	6	6	5	5	
- HNO_3 addition[7]	0.050	0	0	0	0	0	0	0	
- anaerobic storage[8]	0.001	378	410	366	400	392	298	304	
Used as fertilizer[9]		287	305	283	319	346	227	227	
- surface appl. min.soil	0.010	249	265	246	258	241	0	0	
- surface appl. org. soil	0.020	37	40	37	39	36	0	0	
- injection etc.	0.020	0	0	0	23	68	227	227	
NH_3 emission manure[10]	0.010	185	190	156	161	120	62	47	
NH_3 emission fertilizer[11]	0.010	8	10	9	9	8	3	3	
Legumes[12]	0.010	5	13	15	13	11	11	10	
Leaching, run-off etc.[13]	0.010	180	180	183	188	183	120	93	

[1] Van der Hoek (1994, pers.comm.); 90% and 10% of fertilizer N used on mineral and organic soil, respectively; [2] Van der Hoek (1994) and Table A-12; [3] Total manure N meadow - NH_3-N meadow (Table A-12); see Table A-14 for urine N : faeces N; [4, 5, 7] 0; [6] All veal calf manure (Van der Hoek, 1994); [8] Manure N produced in stables, excluding deep litter stables, aerobic storage, or biologically treated (Van der Hoek, 1994); [9] For % injection see Table A-14; 13% of agricultural land is organic soil; [10, 11] Table A-12; [12] 1990 from RIVM (1993a); other years change as areas from Table A-11; [13] Appendix 6-5; [14] Method II emission factors (Table 4-9); for natural background emissions in Gg N y^{-1} (Dutch total); for anthropogenic background emissions in kg N_2O-N ha^{-1} y^{-1}; for other in fraction of N flux.

Table A-16. Activity data (in Gg N y^{-1} unless mentioned otherwise) and emission factors (as fraction of N flux unless mentioned otherwise) for agriculture for the period 2000 - 2015; MV3a (current policy, including "derde fase mestbeleid"), NMP-2 (National Environmental Policy Plan 2) and AP (additional policy)

	Emission factor[14]	2000 MV3a/NMP2	2010 MV3a/NMP2	2015 MV3a/NMP2	2000 AP[15]	2010 AP[15]	2015 AP[15]
Background emissions							
Natural	1.5						
Anthropogenic							
- grassland on organic soil	10.0	as 1990	as 1990	as 1990	as 1990	as 1990	as 1990
- grassland on mineral soil + arable	1.0	as 1990	as 1990	as 1990	as 1990	as 1990	as 1990
Synthetic fertilizer use (excl. NH_3)							
- on mineral soil[1]	0.010	184	157	as 2010	166	142	as 2010
- on organic soil[1]	0.020	20	17		18	16	
Total[2]		205	175		184	157	
Manure excl. NH_3							
Meadow		106	101		as 2000	as 2010	as 2015
- urine in meadow[3]	0.020	53	50		MV3a	MV3a	MV3a
- faeces in meadow[3]	0.010	53	50				
Stable/storage		288	276				
- deep litter stable[4]	0.050	0	0				
- aerobic storage[5]	0.050	0	0				
- biologically treated[6]	0.020	5	5				
- HNO_3 addition[7]	0.050	0	0				
- anaerobic storage[8]	0.001	283	271				
Used as fertilizer[9]		164	163				
- surface appl. min.soil	0.010	0	0				
- surface appl. org. soil	0.020	0	0				
- injection etc.	0.020	164	163				
NH_3 emission manure[10]	0.010	56	43		as 2000	as 2010	as 2015
NH_3 emission fertilizer[11]	0.010	3	3		MV3a	MV3a	MV3a
Legumes[12]	0.010	11	10				
Leaching, run-off, etc.[13]	0.010	120	88		114	84	84

Notes 1 - 14: see table A-15; [15] Additional policy includes options g.1 and g.2 (dessication abatement, resulting in 10% lower background emissions) and h.3 - h.7 (a further reduction of synthetic fertilizer use by 10% relative to NMP-2); see Table 5-7

Appendix 6-5. Activity data for N loading to surface waters

Table A-17. Nitrogen loading (Gg N y^{-1}) to surface waters for the period 1980 - 1992 and MV3 (pre-current policy) projections for 2000 - 2015[1]

	1980	1985	1990	1991	1992	2000 MV3	2010 MV3	2015 MV3
Agriculture	180	180	183	188	183	120	93	as 2010
Industry	16	16	12	12	11	8	9	
Wastewater treatment plants	38	38	39	42	40	21	19	
Atmospheric deposition	15	15	18	17	17	12	11	
Other	17	17	6	5	4	1	1	
Total	266	266	258	264	255	162	133	

[1] 1985, 1990, 2000, and 2010: RIVM (1993a) and atmospheric deposition data from Verstappen (pers.comm.); 1980 is assumed to be as 1985; 1991 and 1992 data for agriculture increase with fertilizer use; 1980, 1990, 1991 data for wastewater treatment are from Peek (pers.comm.); 1991 and 1992 industry, atmospheric deposition and "other" are extrapolations.

Table A-18. Nitrogen loading surface waters (Gg N y^{-1}) for the period 2000 - 2015 for MV3a (current policy), NMP-2 (National Environmental Policy Plan 2) and AP (additional policy)

	2000[1] MV3a/NMP-2	2010[1] MV3a/NMP-2	2015 MV3a/NMP-2	2000 AP[2]	2010 AP[2]	2015 AP
Agriculture	120	88	as 2010	114	84	as 2010
Industry	7	8		7	8	
Wastewater treatment plants	21	19		21	19	
Atmospheric deposition	12	11		12	11	
Other	0	0		0	0	
Total	160	126		154	122	

[1] RIVM (1993b) and Table A-17 for atmospheric deposition; [2] A 5% reduction relative to NMP-2 projections as a result of reduction options h.3 - h.7; see Table 5-7.

Appendix 6-6. Activity data for waste.

Table A-19. Wastewater treatment plants: nitrogen removal (Gg N y^{-1}), related N_2O emissions (Gg N_2O-N y^{-1}) for 1980 - 1992 and projections for 2000 - 2015 as used in the MV3a, NMP-2, and AP projections

	1980	1985	1990	1991	1992	2000	2010	2015
N influent	70.1	70.1	80.9	84.6	83.6	88.2	88.2	as 2010
N effluent	37.7	37.7	39.3	41.5	40.4	21.0[2]	19.0[2]	
N sludge	12.6	12.6	15.9	16.7	16.3	17.0	17.3	
N removal[1]	19.8	19.8	25.7	26.4	26.9	50.2	51.9	

[1] removal = influent - (effluent + sludge); [2] RIVM (1993b), other data from Peek (pers.comm) or 1980 = 1985 or 2010 = 2000.

Table A-20. Incineration of waste (10^3 ton y^{-1}) and related N_2O emissions (Gg N_2O-N y^{-1}); 2000 - 2015: MV3 = MV3a; NMP-2 used for AP

	1980	1985	1990	1991-92[3]	2000	2010	2015
					MV3a	MV3a	MV3a
Waste incineration[1]	1900	3000	3400	3400	6300	9800	10800
N_2O emissions[2]	0.02	0.04	0.04	0.04	0.08	0.12	0.14
					NMP-2	NMP-2	NMP-2
Waste incineration[1]					6990	10970	10800
N_2O emissions NMP-2[2]					0.09	0.14	0.14
N_2O emissions AP[3]					0.04	0.07	0.07

[1] RIVM (1993a) and Van Amstel et al. (1994); 1991/92 assumed to be equal to 1990; [2] Method II emission factors, 12.7 g N_2O-N per ton MSW, see Table 4-12; [3] Reduction option m.1 (optimization of incineration), see Table 5-7.

Appendix 6-7. Activity data for "other" N_2O emissions and NOx emissions

Table A-21. NOx emissions (Gg N y^{-1})[1] for 1980 - 1992 and MV3a (current policy) projections for 2000 - 2015

	1980	1985	1990	1991	1992	2000 MV3a	2010 MV3a	2015 MV3a
Transport	92	92	96	96	96	69	69	as 2010
Industry	28	28	28	28	28	15	13	
Power plants	24	24	22	22	22	9	5	
Refineries	4	4	6	6	6	4	3	
Other	27	27	23	23	23	18	10	
Total	175	175	175	175	175	115	100	

[1] 1985, 1990, 2000, 2010: RIVM (1993b); 1980 = 1985; 1991 = 1992 = 1990; 2015 = 2010

Table A-22. NOx emissions (Gg N y^{-1})[1] for 2000 - 2015; NMP-2 (National Environmental Policy Plan 2) and AP (additional policy)

	2000 NMP-2	2010 NMP-2	2015 NMP-2
Transport	68	50	as 2010
Industry	13	7	
Power plants	9	5	
Refineries	4	1	
Other	17	6	
Total	111	69	

[1] 1985, 1990, 2000, 2010: RIVM (1993b); 1980 = 1985; 1991 = 1992 = 1990; 2015 = 2010

Table A-23. Activity data for "other" N_2O emissions for 1980 - 1992 and MV3a (current policy) projections for 2000-2015

	1980	1985	1990	1991	1992	2000 MV3a	2010 MV3a	2015 MV3a
Atmospheric formation								
- NH_3 emission (Gg N y^{-1})[1]	207	213	177	182	140	77	62	62
Non-agricultural N loading surface waters								
- N input[2]	71	71	57	59	55	30	29	29
Atmospheric deposition[3] (Gg N y^{-1}) of								
- non-agricultural NH_3[1]	14	13	13	12	12	12	12	12
- non-energy NOx[4]	54	54	51	51	51	33	23	23
Anaesthesia (Gg N y^{-1})[5]	0.33	0.33	0.33	0.33	0.33	0.39	0.43	0.45

[1] see Table A-12; [2] see Table A-17 (industry + wastewater treatment plants + other); [3] N_2O emissions are calculated from NOx and NH_3 emissions; [4] see Table A-21 (industry + other); [5] 1990 emission = 1990 use (Duyzer, pers.comm.), 1980-1985 and 1991-1992 set equal to 1990; 2000-2015 increase as nitric acid production (Table A-10).

Table A-24. Activity data for "other" N_2O emissions for 2000 - 2015; MV3a, NMP-2, AP

	2000 NMP-2/AP	2010 NMP-2/AP	2015 NMP-2/AP
Atmospheric formation			
- NH_3 emission (Gg N y^{-1})[1]	71	58	58
Non-agricultural N loading surface waters			
- N input[2] (Gg N y^{-1})	28	27	27
Atmospheric deposition[3] (Gg N y^{-1}) of			
- non-agricultural NH_3[1]	12	12	12
- non-energy NOx[4]	30	13	13
Anaesthesia (Gg N y^{-1})[5]	0.39	0.43	0.45

[1] see Table A-13; [2] see Table A-18 (industry + waste water treatment plants + other); [3] N_2O emissions are calculated from NOx and NH_3 emissions; [4] see Table A-22 (industry + other); [5] As in Table A-23.