



Drawing Down N₂O

To Protect Climate and the Ozone Layer

A UNEP Synthesis Report



Published by the United Nations Environment Programme (UNEP), November 2013

Copyright © UNEP 2013

ISBN: 978-92-807-3358-7

DEW/1748/NA

This publication may be reproduced in whole or in part and in any form for educational or non-profit services without special permission from the copyright holder, provided acknowledgement of the source is made. UNEP would appreciate receiving a copy of any publication that uses this publication as a source.

No use of this publication may be made for resale or any other commercial purpose whatsoever without prior permission in writing from the United Nations Environment Programme. Applications for such permission, with a statement of the purpose and extent of the reproduction, should be addressed to the Director, DCPI, UNEP, P. O. Box 30552, Nairobi 00100, Kenya.

Disclaimers

Mention of a commercial company or product in this document does not imply endorsement by UNEP or the authors. The use of information from this document for publicity or advertising is not permitted. Trademark names and symbols are used in an editorial fashion with no intention on infringement of trademark or copyright laws.

We regret any errors or omissions that may have been unwittingly made.

© Images and illustrations as specified.

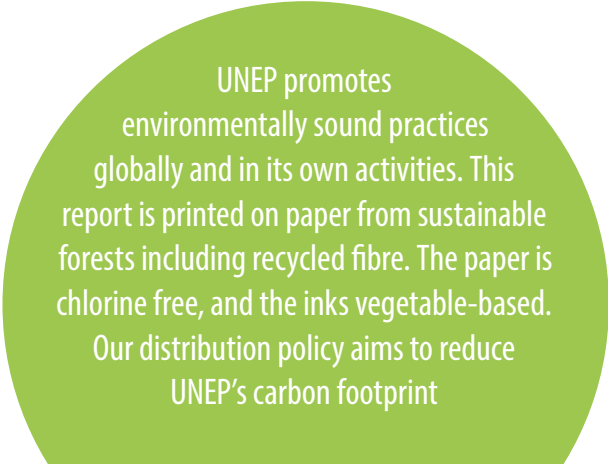
Cover Images: All images from Shutterstock. Forest fire: Peter J. Wilson; Agriculture collage: Symbiot; Coal fire plant: Gary Whitton; Atmosphere: Andrew Armyagov.

Citation

This document may be cited as:

UNEP 2013. Drawing Down N₂O to Protect Climate and the Ozone Layer. A UNEP Synthesis Report. United Nations Environment Programme (UNEP), Nairobi, Kenya

A digital copy of this report can be downloaded at <http://www.unep.org/publications/ebooks/UNEPN2Oreport/>



UNEP promotes environmentally sound practices globally and in its own activities. This report is printed on paper from sustainable forests including recycled fibre. The paper is chlorine free, and the inks vegetable-based. Our distribution policy aims to reduce UNEP's carbon footprint



UNEP

Drawing Down N₂O

To Protect Climate and the Ozone Layer

A UNEP Synthesis Report

November 2013

Acknowledgements

The United Nations Environment Programme (UNEP) would like to thank the Steering Committee, the Lead and Contributing Authors, and the Secretariat for their contribution to the development of this report. The following individuals have provided input to the report. Authors and reviewers contributed to this report in their individual capacity and their organizations are only mentioned for identification purposes.

Steering Committee – Joseph Alcamo, Chair (UNEP); Mateete Bekunda (International Institute of Tropical Agriculture, IITA, Tanzania); Mercedes Bustamante (Universidade de Brasília, Brazil); Marco Gonzalez (UNEP Ozone Secretariat, Kenya); Raymond Knighton (National Institute of Food and Agriculture, US Department of Agriculture); Shamila Nair-Bedouelle (UNEP OzonAction, France); A. R. Ravishankara (National Oceanic and Atmospheric Administration, USA); Rajendra Shende (TERRE Policy Centre, India); Mark A. Sutton (NERC Centre for Ecology and Hydrology, UK); Clifford Snyder, (International Plant Nutrition Institute, USA); Jan van Bergen (Ministry of Infrastructure and the Environment, The Netherlands).

Lead Authors – Lex Bouwman (PBL Netherlands Environmental Agency / Utrecht University, Netherlands); John S. Daniel (National Oceanic and Atmospheric Administration, USA); Eric A. Davidson (Woods Hole Research Center, USA); Cecile de Klein (AgResearch Invermay, New Zealand); Elisabeth Holland (University of the South Pacific, Fiji); Xiaotang Ju (China Agricultural University, P.R. of China); David Kanter (Princeton University, USA); Oene Oenema (Wageningen University, The Netherlands); A. R. Ravishankara, *Part 1 Coordinator* (National Oceanic and Atmospheric Administration, USA); Ute M. Skiba (NERC Centre for Ecology and Hydrology, UK); Sietske van der Sluis (PBL Netherlands Environmental Agency, Netherlands); Mark A. Sutton, *Part 2 Coordinator* (NERC Centre for Ecology and Hydrology, UK); Guido R. van der Werf (VU University Amsterdam, The Netherlands); Timothy J. Wallington (Ford Motor Company, USA); Peter Wiesen (University of Wuppertal, Germany); Wilfried Winiwarter (International Institute of Applied Systems Analysis / University of Graz, Austria).

Contributing Authors – Marta Alfaro (Institute for Agricultural Research, Chile); Paulo Artaxo (University of São Paulo, Brazil); Kristie Boering (University of California, USA); Agustin del Prado (BC3 Basque Centre for Climate Change, Spain); Bing Gao (China Agricultural University, P.R. of China); Carolien Kroeze (Wageningen University, The Netherlands); Jan Peter Lesschen (Wageningen University, The Netherlands); Lin Ma (Wageningen University, The Netherlands); Rob Maas (RIVM, National Institute for Public Health and the Environment, The Netherlands); C. P. Meyer (CSIRO Marine and Atmospheric Research, Australia); Sandor Mulsow (Universidad Austral de Chile, Chile); Himanshu Pathak (Indian

Agricultural Research Institute, India); Priya Sharma (University of the South Pacific, Fiji); Emma Suddick (Woods Hole Research Center, USA); Parvatha Suntharalingam (University of East Anglia, UK); Sirintornthep Towprayoon (King Mongkut's University of Technology, Thailand); Hans J. M. van Grinsven (PBL Netherlands Environmental Assessment Agency, The Netherlands); Gerard Velthof (Wageningen University, The Netherlands); Gui-Ling Zhang (Ocean University of China, P.R. of China); Xunhua Zheng (LAPC, Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), P.R. of China).

Reviewers – Zucong Cai (Nanjing Normal University, P.R. of China); Martyn Chipperfield (University of Leeds, UK); Lei Duan (Tsinghua University, P.R. of China); Jan Willem Erisman (Louis Bolk Institute and VU University Amsterdam, The Netherlands); Jonathan E. Hickman (The Earth Institute at Columbia University, USA); Melanie Miller (Touchdown Consulting, Belgium); Arvin R. Mosier (USDA/ARS Retired, USA); Cynthia Nevison (University of Colorado/INSTAAR, USA); Stephen Ogle (Colorado State University, USA); Braulio Pikman (Environmental Resources Management, Brazil); Dave S. Reay (University of Edinburgh, UK); Claire E. Reeves (University of East Anglia, UK); Johan Six (ETH-Zurich, Switzerland); Keith A Smith (University of Edinburgh, UK); Guus J.M. Velders (RIVM, National Institute for Public Health and the Environment, The Netherlands); Rodney T. Venterea (USDA-Agricultural Research Service, USA); Xin Zhang (Woodrow Wilson School, Princeton University, USA).

Editorial Team – Joseph Alcamo (UNEP); Sunday A. Leonard (UNEP); A. R. Ravishankara (National Oceanic and Atmospheric Administration, USA); Mark A. Sutton (NERC Centre for Ecology and Hydrology, UK).

Project Management – Sunday A. Leonard (UNEP)

UNEP Secretariat and Media Support – Harsha Dave; Linda Duquesnoy; Melissa Gorelick; Michael Logan; Kelvin Memia; Nick Nuttal; Neeyati Patel; Ron Witt; Shereen Zorba.

Design, Layout and Production – Pauran Ghaffarpour; Eugene Papa (United Nations Office at Nairobi).

Printing – UNON, Publishing Services Section, ISO 14001:2004 - certified.

UNEP and the authors of this report would also like to thank the following individuals and organizations for their valuable comments and valuable advice and support: Agnieszka Becher (NERC Centre for Ecology and Hydrology); Tami C. Bond (University of Illinois at Urbana-Champaign, USA); Anjan Datta (UNEP); Greg Fiske (Woods Hole Research Center, USA); Susan Greenwood (Scientific Committee on Problems of the Environment); Clare Howard (NERC Centre for Ecology and Hydrology / University of Edinburgh, UK); Fatoumata Keita-Ouane (UNEP); Barbara Lubkert; Simon Martin (UNEP); Kate E. Mason (NERC Centre for Ecology and Hydrology); Oluwaseun P. Oluyide (RETRIDAL – National Open University of Nigeria); the European Commission (ÉCLAIRE and NitroEurope projects); International Nitrogen Initiative; Natural Environment Research Council, UK; the UNECE CLRTAP Task Force on Reactive Nitrogen; Global Partnership on Nutrient Management and the US National Science Foundation Research Coordination Network on Reactive Nitrogen, Grant DEB-1049744.

Contents

Glossary, Acronyms and Abbreviations	v
Foreword	viii
Executive Summary	ix
Chapter 1 Introduction	1
1.1. Background	1
1.2. Objective of Report	2
Part 1 The Nitrous Oxide Challenge.....	3
Chapter 2 N₂O: Its Role in Climate Change and Ozone Layer Depletion	4
2.1. Increasing concentration of N ₂ O in the atmosphere	4
2.2. Role of N ₂ O in climate change and ozone layer depletion	5
2.3. Continuing N ₂ O emissions: implication for climate and the ozone layer	8
2.4. Conclusions.....	8
Chapter 3 N₂O: Sources, Inventories, Projections	9
3.1. Introduction	9
3.2. Natural emissions	9
3.3. Anthropogenic emissions	10
3.4. Trends in emissions over the last 20 years	13
3.5. Emission projections	13
3.6. Conclusions	14
Part 2 Solutions to the N₂O Challenge	16
Chapter 4 Reducing N₂O Emissions from Agricultural Sources.....	17
4.1. Introduction	17
4.2. Sources of N ₂ O emissions from agriculture	17
4.3. Options for emission reductions.....	18
4.4. Co-benefits, success stories and challenges	22
4.5. Estimating emission reduction potential	22
4.6. Conclusions	25
Chapter 5 Reducing N₂O Emissions from Industry and Fossil Fuel Combustion.....	26
5.1. Introduction	26
5.2. Stationary combustion sources	26
5.3. N ₂ O emissions from mobile combustion	27
5.4. N ₂ O emissions from industrial processes	28
5.5. Conclusions.....	31
Chapter 6 Reducing N₂O Emissions from Biomass Burning in Landscape Fires and Household Stoves	32
6.1. Introduction	32
6.2. N ₂ O Emissions from biomass burning.....	32
6.3. Options for emission reductions	33
6.4. Successful examples of emission reductions	35
6.5. Potential emission reductions	35
6.6. Unresolved questions	36
6.7. Conclusions.....	36
Chapter 7 Reducing N₂O Emissions from Wastewater and Aquaculture.....	37
7.1. Introduction.....	37
7.2. Wastewater.....	37
7.3. Aquaculture	40
7.4. Conclusions	41
Chapter 8 Drawing-Down N₂O Emissions: Scenarios, Policies and the Green Economy	42
8.1. The N ₂ O challenge	42
8.2. Scenarios for reducing N ₂ O emissions	42
8.3. Relevance of reduced N ₂ O emissions for protecting climate and the ozone layer	43
8.4. Realizing N ₂ O reduction potential through the green economy.....	45
8.5. Embedding N ₂ O mitigation in international governance	47
8.6. Conclusions.....	49
References.....	50

Glossary, Acronyms and Abbreviations

Glossary

Aerosols – are collections of airborne solid or liquid particles with a typical size between 0.01 and 10 micrometre. They may influence the climate directly by scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds.

Annex I Countries – the industrialised countries (and those in transition to a market economy) which took on obligations to reduce their greenhouse gas emissions under the United Nations Framework Convention on Climate Change.

Atmospheric Deposition – removal of suspended material from the atmosphere, classed as either ‘wet’ or ‘dry’. Wet deposition occurs when material is removed from the atmosphere by precipitation. In dry deposition, gases and particles are removed from the atmosphere by contact with a surface.

Atmospheric Lifetime – the time it takes for 63% of the abundance of a chemical to be removed from the atmosphere in the absence of emissions.

Atmospheric Nitrogen – a molecule also called dinitrogen (N_2), which contains two nitrogen atoms. It is an inert and harmless gas not usable by most life forms. It makes up 78% of the volume of the atmosphere.

Biofuels – non-fossil fuels (e.g. biogas, biodiesel, bioethanol). They are energy carriers that store the energy derived from organic materials (biomass) including plant materials and animal waste.

Biological Nitrogen Fixation (BNF) – the process of converting atmospheric nitrogen (N_2) by bacteria, fungi, and blue-green algae into reactive forms, usable by plants and animals, including humans.

Black Carbon – a form of air pollution consisting of carbon particles produced by incomplete combustion of fuels. It is produced especially by diesel-powered vehicles, open biomass burning, cooking stoves and other sources.

Business-As-Usual (BAU) – a scenario used for projections of future emissions assuming no action, or no new action, is taken to mitigate emissions.

Carbon Credits – tradeable permits that aim to reduce greenhouse gas emissions by giving them a monetary value.

Carbon Dioxide Equivalent (CO_2e) – a simple way to place

emissions of various climate change agents on a common footing to account for their effect on climate. It describes, for a given mixture and amount of greenhouse gases, the equivalent weight of carbon dioxide that would have the same global warming ability, when measured over a specified timescale.

Carbon Leakage – according to the Intergovernmental Panel on Climate Change, carbon leakage occurs when there is an increase in carbon dioxide emissions in one country as a result of an emissions reduction by a second country. For example, an increase in local fossil fuel prices resulting from mitigation policies may lead to the re-allocation of production to regions with less stringent mitigation rules (or with no rules at all), thus causing higher emissions in those regions.

Certified Emission Reductions (CERs) – emission reductions from CDM project activities in accordance with the CDM rules and requirements, which are expressed in units equal to one metric tonne of carbon dioxide equivalent, calculated using global warming potentials defined by Decision 2/CP.3 of the United Nations Framework Convention on Climate Change or as subsequently revised in accordance with Article 5 of the Kyoto Protocol.

Clean Development Mechanism (CDM) – one of the three market-based mechanisms under the Kyoto Protocol to the United Nations Framework Convention on Climate Change, whereby developed countries may finance greenhouse gas emission-avoiding projects in developing countries, and receive credits for doing so, which they may apply towards meeting mandatory limits on their own emissions.

Denitrification – the microbial regeneration of dinitrogen (N_2) or nitrous oxide (N_2O) from nitrate (NO_3^-). N_2O represents an intermediary on the overall pathway of denitrification to form N_2 .

Dobson Unit (DU) – a common unit used to measure overhead column ozone amounts. One DU is the number of molecules of ozone that would be required to create a layer of pure ozone 0.01 millimeters thick at a temperature of 0°C and a pressure of 1 atmosphere (the air pressure at the surface of the Earth).

Emission Factor (EF) – a representative value that relates the quantity of a pollutant released to the atmosphere with the activity associated with its release. The EF is used in estimating emissions from various sources of air pollution using the formula: Emissions = EF x Activity.

Eutrophication – the over-fertilization of an aquatic ecosystem by inorganic nutrients (e.g. nitrate, phosphate). This may occur naturally or through human activity (e.g., from fertilizer runoff and sewage discharge). It typically promotes excessive growth of algae, which could result in the depletion of available dissolved oxygen.

Feed Conversion Ratio – measure of the efficiency of how animals (livestock or fish) convert feed mass to body mass. It provides an indication of how much feed is required to achieve a specified body mass.

Global Warming Potential (GWP) – a relative index that enables comparison of the climate effect of the emissions of various greenhouse gases (and other climate changing agents). Carbon dioxide, the greenhouse gas that causes the greatest anthropogenic radiative forcing because of its overwhelming abundance, is chosen as the reference gas. GWP is also defined as an index based on the radiative forcing of a pulsed injection of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere, integrated over a chosen time horizon, relative to the radiative forcing by a unit mass of carbon dioxide over the same time horizon. The GWPs represent the combined effect of the differing atmospheric lifetimes (i.e., how long these gases remain in the atmosphere) and their relative effectiveness in altering the energy balance at the tropopause. The Kyoto Protocol uses GWPs from pulse emissions over a 100-year time horizon.

Haber-Bosch Process – a high pressure chemical process which synthesizes reactive nitrogen as ammonia (NH_3) from the reaction of N_2 and H_2 .

Joint Implementation (JI) – projects that allow a country with an emission reduction or limitation commitment under the Kyoto Protocol (Annex B Party) to earn emission reduction units (ERUs) from an emission reduction or emission removal project in another Annex B Party. Each ERU is equivalent to one tonne of CO_2 , which can be counted towards meeting its Kyoto target.

Kyoto Protocol – the international Treaty intended to reduce greenhouse gas emissions. It adds additional provisions to the United Nations Framework Convention on Climate Change.

Leaching – the washing out of soluble ions and compounds by water draining through soil.

Leguminous Plants – plants that are able to fix nitrogen from the atmosphere due to root nodules, which contain rhizobia bacteria, which act with the plant in a symbiotic relationship. Legumes can be used by farmers to replenish the reactive nitrogen levels in the soil in a crop rotation sequence.

Mixing Ratio – a metric commonly used in the atmospheric sciences to indicate the concentration of a trace gas in air. It is defined as the fractional number of moles of a trace gas such as N_2O , contained in one mole of air. In the atmosphere, this is also equivalent to the volume of a trace gas per volume of air. It is typically expressed in units of parts per billion (ppb) or parts per million (ppm).

Montreal Protocol – the multilateral environmental agreement dealing with the depletion of the Earth's stratospheric ozone layer.

Nitrates Directive – a European Commission Directive (1991) which regulates agricultural practices that can lead to losses of nitrate to the environment.

Nitrification – a two-step process, carried out mostly by microorganisms in soils and water bodies, involving the oxidation of NH_4^+ to NO_2^- which is then further oxidized to NO_3^- .

Nitrogen Fixation – a process through which inert dinitrogen (N_2) is converted to reactive nitrogen forms such as ammonia (NH_3) and nitrates (NO_3). Nitrogen is fixed in nature by microorganisms or lightning. It is referred to as biological nitrogen fixation when it is performed by microorganisms (see Biological Nitrogen Fixation).

Nitrogen Use Efficiency (NUE) – A measure of performance in converting inputs of nitrogen compounds into useful products. There are several ways of expressing NUE, with the simplest being the amount of nitrogen in a product divided by the amount of nitrogen used, often expressed as a percentage.

Non-Annex I Countries – a group of developing countries that have signed and ratified the United Nations Framework Convention on Climate Change. They do not have binding emission reduction targets.

Ozone Depleting Substances – refers to substances that can deplete the stratospheric ozone layer and that are listed in the Montreal Protocol.

Ozone Depletion Potential (ODP) – a measure of the extent of stratospheric ozone layer depletion by a given ozone depleting substance, relative to that depleted by an equivalent mass of CFC-11. (CFC-11 has an ODP of 1.0).

Radiative Forcing – a measure of how a climate forcing agent influences the Earth's energy balance, with a positive value indicating a net heat gain to the lower atmosphere (warming), and a negative value a decrease (cooling).

Reactive Nitrogen – collectively any chemical form of nitrogen other than dinitrogen (N_2). Reactive nitrogen (N_r) compounds include NH_3 , NO_x , N_2O , NO_3^- and many other chemical forms, and are involved in a wide range of chemical, biological and physical processes.

Root-Exudates – Substances released from a plant root system in drops or small quantities containing carbohydrates, organic acids, vitamins and many other substances essential for life of soil microorganisms.

Scenario – a description of how the future may unfold based on 'if-then' propositions. Climate change scenarios typically include an initial socio-economic situation and a description of the key driving forces and future changes in emissions, temperature, or other climate change-related variables.

Sewage Sludge – residual, semi-solid material left from sewage treatment processes.

Stratospheric Ozone – ozone (O_3) present in the stratosphere, which is located between roughly 15 and 50 km above the Earth's surface.

Stratospheric Ozone Depletion – depletion of ozone in the stratosphere (the second layer of the atmosphere, located

above the ‘troposphere’). This depletion allows increased levels of UVB (a harmful form of ultraviolet radiation) to reach the earth’s surface. When the depletion is strong in a specific area, it is commonly referred to as an ‘ozone hole’.

Synthetic Fertilizer – fertilizer produced industrially typically using the ‘Haber–Bosch’ process.

Teragrams N₂O-N/yr (Tg N₂O-N/yr) – the units used in this report to describe emissions of nitrous oxide (Tg N₂O-N/yr). This means teragrams (10¹² grams) of nitrous oxide in equivalent nitrogen units per year.

Troposphere – the lowest portion of the earth’s atmosphere, the depth of which varies geographically, being thickest at the tropics and shallowest at the poles.

Tropospheric Ozone – refers to ozone in the troposphere.

Urea – a reactive nitrogen form, urea (or carbamide) is an organic compound with the chemical formula (NH₂)₂CO.

Urea is widely used in fertilizers as a convenient source of nitrogen. It is also an important raw material for the chemical industry.

Volatile Organic Compounds (VOCs) – organic compounds present in the atmosphere in gaseous form although they are commonly liquids or solids, e.g., benzene. They easily vaporise at room temperature.

Well-mixed Gases – a term used for gases that have lifetimes long enough to be relatively homogeneously mixed in lower part of the atmosphere. Hence, their impact on climate and ozone depletion does not depend on where in the atmosphere they are emitted. Measurements of such a gas in one remote surface location will be almost identical to measurements in any other remote location. It should be noted that well-mixed gases may still demonstrate concentration variations in non-remote locations, particularly near large source or sink regions.

Acronyms and Abbreviations

AR4	IPCC Fourth Assessment Report	N₂	Inert Nitrogen Gas
BAU	Business-As-Usual	N₂O	Nitrous Oxide
BNF	Biological Nitrogen Fixation	NCO	Isocyanate Group
CBD	United Nations Convention on Biological Diversity	NH	Imidogen Group
CCAC	Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants	NH₃	Ammonia
CDM	Clean Development Mechanism	NO_x	Nitrogen Oxides
CERs	Certified Emissions Reductions	N_r	Reactive Nitrogen
CFCs	Chlorofluorocarbons	NSCR	Non-Selective Catalytic Reduction
(CH₂)₄(COOH)₂	Adipic acid	NUE	Nitrogen Use Efficiency
CH₄	Methane	O₃	Ozone
CLRTAP	Convention on Long-range Transboundary Air Pollution, under the United Nations Economic Commission for Europe	ODP	Ozone Depletion Potential
EU-ETS	the EU-Emissions Trading System	ODS	Ozone Depleting Substance
FAO	Food and Agriculture Organization of the United Nations	ppb	parts per billion
GEF	Global Environment Facility	RCP	Representative Concentration Pathway
GFED	Global Fire Emissions Database	SLCPs	Short-Lived Climate Pollutants
HCN	Hydrogen Cyanide	SRES	The Special Report on Emissions Scenarios
HFCs	Hydrofluorocarbons	Tg	Teragram
HNO₃	Nitric Acid	UNECE	United Nations Economic Commission for Europe
INPE	Brazilian National Institute for Space Research	UNEP	United Nations Environment Programme
IPCC	Intergovernmental Panel on Climate Change	UNFCCC	United Nations Framework Convention on Climate Change
JI	Joint Implementation	VOCs	Volatile Organic Compounds
LULUCF	Land Use, Land Use Change, and Forestry	WALFA	Western Arnhem Land Fire Abatement
		WMO	World Meteorological Organization

Foreword



Perhaps you have never heard of nitrous oxide, a gas that is both a potent pollutant in respect to damaging the ozone layer and one that is contributing to climate change?

If the environmental, economic and health challenges linked with these two global threats are to be addressed, then nitrous oxide needs to be better known, and more importantly, addressed.

Both issues require a comprehensive understanding of the drivers of environmental degradation and the multiple, cost effective pathways to an answer.

While nitrous oxide is naturally present in the Earth's atmosphere in trace amounts, human activities have been increasing its concentrations since the industrial revolution.

This synthesis report, coordinated by UNEP, working with more than 45 scientists and experts from more than 35 organizations, concludes that emissions of nitrous oxide are now the most relevant with respect to stratospheric ozone depletion and the third most important gas in terms of climate change. The report shows that if current trends in nitrous oxide emissions are allowed to continue, then it is

very possible that ozone layer depletion will continue even with other efforts being implemented.

But the report also comes with some good news – with the right determination and commitment to act, it is possible to bring down nitrous oxide emissions. Several readily available technologies and measures exist today for reducing nitrous oxide emissions from the different economic sectors concerned.

Reducing nitrous oxide emissions also comes with other added benefits – nitrous oxide emissions are connected to many different economic sectors including agriculture, chemical manufacturing, electricity production, waste management, transportation and fish production. Hence, gains will include increased crop and livestock productivity, poverty alleviation, improved human health and reduced environmental degradation – all of which are in keeping with the transition towards an inclusive green economy.

Despite increasing penetration of renewable energies, improvements in energy efficiency, investments in forests and other ecosystems and legions of voluntary actions such as those to reduce black carbon, greenhouse gas emissions continue to climb putting the world and its people at increasing risk of dangerous climate change.

In order to avert this, greater ambition is needed by nations across a suite of challenges. Recognizing the impact of nitrous oxide on both the climate and the ozone layer and taking steps to address this pollutant offers another promising pathway to keep humanity's footprint on our planet within sustainable limits.

A handwritten signature in black ink, reading 'Achim Steiner'. The signature is fluid and cursive, with a large initial 'A'.

Achim Steiner
UN Under-Secretary-General,
UNEP Executive Director

Executive Summary

This report addresses the benefits of drawing down nitrous oxide (N₂O) emissions. N₂O is now the most significant ozone-depleting substance emission and the third most important greenhouse gas released into the atmosphere.

Global anthropogenic N₂O emissions are rapidly increasing and are expected to almost double by 2050 unless mitigation action is accelerated. The continued build-up of N₂O in the atmosphere will continue to deplete the stratospheric ozone layer and in so doing will to a degree undermine the achievements of the Montreal Protocol. The build-up of N₂O will also make it more difficult to achieve climate targets.

Two-thirds of current anthropogenic N₂O emissions originate from agriculture and these can be reduced by boosting nitrogen use efficiency, especially by making the use of fertilizer, manure and feed more efficient. Improving nitrogen use efficiency can be accomplished through a wide variety of feasible options. This would bring added benefits of higher crop and livestock productivity, lower required agriculture inputs, as well as reduced air and water pollution due to decreased nitrogen losses to the environment. Small, but quick gains may also be possible by controlling emissions from just two chemical industries (adipic acid and nitric acid) that account for about 5% of global gross¹ anthropogenic emissions.

1. Why are we concerned about nitrous oxide in the atmosphere?

Human activities are resulting in a steady increase of N₂O in the atmosphere. If abatement action is not taken, N₂O emissions could almost double by 2050.

Since the pre-industrial era, anthropogenic emissions have led to a 20% increase in the level of N₂O in the atmosphere. The best estimate of current total net emissions from human

activities is 5.3 Tg N₂O-N/yr.² Under business-as-usual conditions without additional future mitigation efforts, N₂O emissions are projected to increase by 83% between 2005 and 2050.³

Nitrous oxide is now the most significant ozone-depleting emission to the atmosphere. The presence of high levels of anthropogenic N₂O in the atmosphere will continue to cause ozone layer depletion and, to some extent, undermine the gains of the Montreal Protocol.

Most of the depletion of the stratospheric ozone layer up to now has been due to chlorofluorocarbons (CFCs) and other halogenated (chlorine- and bromine-containing) chemicals. However, N₂O also contributes to this depletion by being the dominant source of nitrogen oxides in the stratosphere and depleting the ozone layer in a way similar to CFCs and other ozone-depleting halocarbons. But unlike these chemicals, N₂O is not controlled by the Montreal Protocol. Nevertheless, when weighted according to its ozone-depleting ability, N₂O is now the most important ozone-depleting emission to the atmosphere. This is mostly because CFCs and other substances have been drastically reduced under the Montreal Protocol, but also because of the steady increase in anthropogenic N₂O emissions.

It is important to note that the reduction in emissions that has already been achieved for most ozone-depleting substances will help stratospheric ozone concentrations to recover to levels found before the 1980s, but that the increasing levels of N₂O in the atmosphere will continue to cause ozone layer depletion. In this respect, the growing concentration of N₂O is to an extent undermining the gains in ozone layer recovery being achieved by the declining atmospheric levels of CFC and other ozone depleting substances.

In terms of global emissions, N₂O is now the third most important greenhouse gas.

¹ Total gross anthropogenic emissions refers to the sum of all emissions that have increased due to human activity. Because land-use change has reduced N₂O emissions from tropical forest soils, the total net anthropogenic emissions are lower than total gross anthropogenic emissions.

² The units used in this report to describe emissions of nitrous oxide are "Tg N₂O-N/yr". This means teragrams (10¹² grams) of nitrous oxide in equivalent nitrogen units per year.

³ This is the mean of business-as-usual estimates from four sets of scenarios reviewed in this report.

Although not as abundant in the atmosphere as CO₂ in terms of mass, N₂O still has an impact on global warming because of its radiative properties and long lifetime in the atmosphere (roughly 120 years). The emission of one kilogramme of N₂O has the global warming potential of the emission of 300 kg of CO₂ when summed over a 100 year period. In terms of its current impact on climate, N₂O is now the third most important greenhouse gas (behind CO₂ and CH₄) emitted into the atmosphere. Because of its increasing anthropogenic emissions, it poses a growing threat to the climate system.

Has enough action been taken against N₂O emissions?

Because N₂O is an important greenhouse gas and ozone depleting substance, it could be argued that not enough action is being taken to combat its build-up in the atmosphere. For example, N₂O is mentioned in the Vienna Convention for the Protection of the Ozone Layer, but not controlled under its Montreal Protocol. In addition, few projects under the Global Environmental Facility address N₂O emissions. Meanwhile, under the Clean Development Mechanism of the United Nations Framework Convention on Climate Change (UNFCCC), action has been taken against N₂O emissions from nitric and adipic acid production, but not from other sectors accounting for the vast majority of emissions. Mitigation options, including opportunities for ramping up international action against N₂O emissions, are discussed in this report.

2. Where does N₂O in the atmosphere come from?

Nitrous oxide has a variety of natural and anthropogenic sources. Increase in anthropogenic emissions is leading to an increase of N₂O in the atmosphere.

Natural emissions including those from terrestrial, marine and atmospheric sources are estimated at roughly 11 Tg N₂O-N/yr (uncertainty range: 10.2 to 12.1). However, these emissions do not lead to a build-up of N₂O in the atmosphere because the atmosphere and biosphere have adjusted to them over a long period of time. A best estimate of current total *gross* anthropogenic emission is 6.2 Tg N₂O-N/yr, while a best estimate of current total *net* anthropogenic emissions is 5.3 Tg N₂O-N/yr (taking into account reduced emissions due to land-use change). Previous assessments have ranged between this value and estimates as high as 8.4 Tg N₂O-N/yr. This report finds that the lower end of the range of previous assessments is the most likely. In any case, the steady increase of these emissions since the industrial revolution has led to a parallel increase of N₂O in the atmosphere unprecedented since the last ice age maximum.

Agriculture is by far the largest source of anthropogenic N₂O emissions (Figure ES.1). Emissions from nitrogen in fertilizers and manures, crop residues, and other agricultural sources currently amount to 4.1 Tg N₂O-N/yr (range: 3.8-6.8), equivalent to about 66%⁴ or two-thirds of total gross anthropogenic emissions.

⁴ Note that the sum of the percentage emissions from the sectors listed here do not add up to 100% because other emission sources such as anthropogenic fluxes of N₂O from the oceans are not included in the summation.

Other important sources of anthropogenic N₂O emissions are industry and fossil fuel combustion, biomass burning, and wastewater.

Industrial and fossil fuel combustion – This category includes emissions from stationary combustion (mainly coal power plants) and mobile combustion sources (road and air transport), as well as emissions from nitric and adipic acid production. Current emissions amount to 0.9 Tg N₂O-N/yr (range: 0.7-1.6) equivalent to about 15% of total gross anthropogenic emissions.

Biomass burning – This category covers two main sources – landscape fires (including forest fires and crop residue burning) and biomass burned in the household for cooking and heating. Current emissions are 0.7 Tg N₂O-N/yr (range: 0.5-1.7), equivalent to about 11% of total gross anthropogenic emissions.

Wastewater and aquaculture – N₂O emissions in this sector arise from wastewater treatment processes, as well as from the discharge of nitrogen wastes to surface waters from sewage and from aquaculture. Current emissions amount to 0.16 Tg N₂O-N/yr (range: 0.02-0.73) for wastewater and 0.05 Tg N₂O-N/yr (range: 0.02-0.24) for aquaculture, together equivalent to about 4% of total gross anthropogenic emissions.

3. What measures can reduce N₂O emissions?

Agricultural emissions can be reduced by boosting the overall nitrogen use efficiency of agriculture as well as by lowering meat consumption and food waste and food losses.

Under business-as-usual conditions, N₂O emissions from agriculture could grow from 4.1 Tg in 2010 to 6.0 Tg N₂O-N/yr by 2020 and to 7.5 Tg N₂O-N/yr by 2050. The increase is from projected growth in nitrogen fertilizer usage and production of animal manure nitrogen associated with meat and dairy products. This projected increase in production is a consequence of both increasing global population and increasing rates of consumption per person.

However, if concerted emission reduction actions are taken, it is possible to reduce N₂O emissions from agriculture by 1.3 Tg N₂O-N/yr in 2020 and by 4.5 Tg N₂O-N/yr in 2050, relative to business-as-usual in those years.

An important and effective strategy to reduce N₂O emissions with many co-benefits is to *improve the nitrogen use efficiency of agriculture*. This means improving the ability of crops and livestock to utilize nitrogen, and minimizing the loss of nitrogen to the environment that occurs during crop cultivation and animal production. The efficiency of nitrogen use can be improved by a wide range of available and feasible methods.

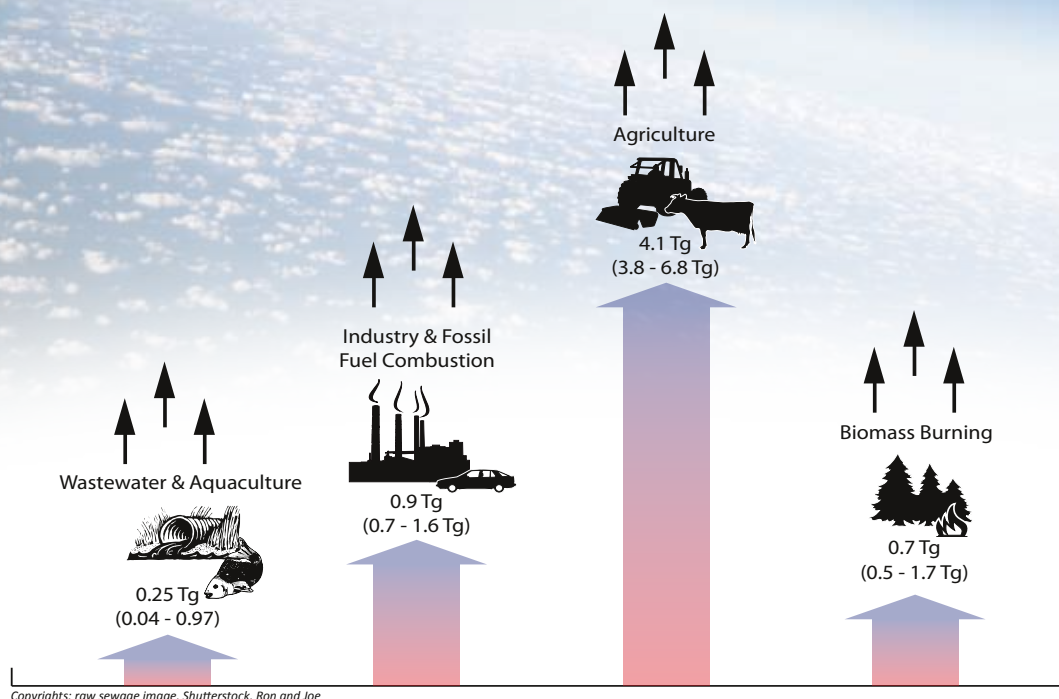
For example, in crop production:

- Nutrient management strategies that ensure the efficient use of animal manure and fertilizer;
- Use of enhanced efficiency fertilizers that increase the uptake of nitrogen by plants and minimize nitrogen losses from the soil;
- Crop husbandry practices that increase crop yield at similar or lower nitrogen use.

In livestock production:

- Animal husbandry practices that lower feed

Figure ES.1 Current anthropogenic N₂O emission sources and estimates of their contributions



requirements per unit animal produced, through animal breeding, improved herd management and improved feed quality and feed management;

- Improved recycling of animal manure to crop land.

The improvement of nitrogen use efficiency comes with important co-benefits discussed later under point 5.

Other options for reducing agricultural emissions of N₂O are:

Reducing excessive meat consumption – Taken as a whole, producing animal protein leads to higher N₂O emissions than plant protein. Therefore, reducing meat consumption, especially in affluent countries where protein consumption is already above dietary needs, would reduce N₂O emissions.

Reducing food waste and losses – A considerable percentage of produced food is either lost or wasted at various stages between production and consumption. Avoiding this loss or wastage could increase farmers' profits, reduce the amount of food that needs to be produced, and thereby reduce emissions associated with food production.

Industrial emissions can be abated by installing N₂O abatement equipment in facilities producing nitric and adipic acid. Emissions from fossil fuel combustion (stationary combustion and transportation) can be reduced by reducing fossil fuel use or applying abatement equipment.

Under business-as-usual conditions, emissions from industry and fossil fuel combustion could grow from 0.9 Tg in 2010 to 1.0 Tg N₂O-N/yr by 2020 and 1.4 Tg N₂O-N/yr by 2050. These increases occur because of projected growth in energy consumption from stationary combustion sectors and growing global demand for fertilizer, nylon, plastics as well as other industrial products.

However, if actions are taken, it is possible to reduce N₂O emissions from industry and stationary combustion by 0.3 Tg N₂O-N/yr in 2020 and 0.9 Tg N₂O-N/yr in 2050 relative to business-as-usual in those years.

Options for achieving these reductions include:

- The installation of N₂O abatement technologies including catalytic and thermal destruction techniques in nitric and adipic acid production.
- The application of catalytic techniques and reducing fossil fuel consumption in stationary combustion sources.

N₂O emissions from mobile fossil fuel combustion (road and air transport) are projected to decline in the business-as-usual scenario as a result of the incorporation of NO_x and VOC emission control technologies for road vehicles.

Industrial emissions are not the largest source of N₂O, yet add up to a significant amount, and may present viable opportunities for reduction over the next few years.

Two industries – adipic acid production and nitric acid production, alone account for about 5% of global gross anthropogenic N₂O emissions. Given the limited number of production plants involved, emission reductions might be easier to achieve here than in sectors having many diffuse emission sources such as in the biomass burning and agriculture sectors.

Significant progress has already been achieved in reducing emissions from adipic acid plants with approximately 80% of capacity in existing plants (as of 2010) already having N₂O abatement technologies. Not as much progress has been made in controlling N₂O from nitric acid plants. A public-

private partnership could be an option for accelerating the adoption of N₂O controls at all adipic and nitric acid plants.

Emissions from biomass burning can be abated by a variety of means depending on the source of emissions.

Because of difficulty in projecting the occurrence of future landscape fires, no estimates are made here for business-as-usual trends for this sector. The best estimate of current emissions (0.7 Tg/yr) is used as a baseline up to 2050. The emission reduction potential relative to this baseline is estimated to be 0.04 Tg N₂O-N/yr in 2020 and 0.26 Tg N₂O-N/yr in 2050.

Emissions from landscape fires can be abated by reducing the use of fires for forest clearing, implementing prescribed burning to lessen the amount of burnable vegetation in natural fires, and decreasing the frequency of unintentional fires.

Emissions from biomass-burning household stoves can be abated, for example, by improving the fuel and combustion efficiency of stoves.

Emissions from wastewater can be abated through various interventions in the collection and treatment of wastewater; emissions from aquaculture can be controlled by intervening in various aquaculture processes.

Under business-as-usual conditions, emissions from wastewater and aquaculture could grow from 0.21 Tg in 2010 to 0.25 Tg N₂O-N/yr by 2020 and 0.37 Tg N₂O-N/yr by 2050. These increases occur because of continued population and economic growth resulting in increased generation of wastewater and growing demand for fish products.

However, if actions are taken, it is possible to reduce N₂O emissions from wastewater and aquaculture by 0.09 Tg N₂O-N/yr in 2020 and 0.15 Tg N₂O-N/yr in 2050.

Emissions from wastewater can be reduced by lowering the nitrogen content of discharge wastewater, reducing wastewater leakage from sewage piping, and recycling nutrients in wastewater as fertilizer.

Emissions from aquaculture can be abated by boosting the overall nitrogen use efficiency of aquaculture, and by implementing fish farming systems that reduce the amount of waste generated during fish production, or by treating effluents from fish ponds.

The individual actions in these different emission sectors can be seen as part of a wider package to improve full-chain nitrogen use efficiency throughout the nitrogen cycle. By combining improvements in process efficiency with improved recycling patterns and societal choices, the overall goal is to increase food, energy and industrial production per unit of new nitrogen fixation, thereby decreasing the amount of N₂O emission per unit of production.

4. What are possible trends in global emissions up to 2050 under different mitigation assumptions?

As noted earlier, under *business-as-usual* assumptions of little or no mitigation, emissions of N₂O could almost double between 2005 and 2050. Meanwhile, scenarios with

moderate mitigation slow the increase over this period and *concerted mitigation* scenarios reverse the upward trend of global N₂O emissions and show a decrease in global emissions between 2005 and 2050.

The potential to reduce N₂O emissions is high over the coming years and decades. The actions taken as part of the concerted mitigation scenarios reduce global N₂O emissions by 26% in 2020 and 57% in 2050 relative to business-as-usual levels in those years.

To examine future trends and the reduction potential of N₂O emissions, four different sets of scenarios were analysed. Besides making different assumptions about the level of mitigation, each of these scenarios made different assumptions about the driving forces of emissions such as population growth and future fertilizer use. The scenarios were clustered into three groups (Figure ES.2):

- *Business-as-usual* scenarios, with little or no mitigation;
- *Moderate mitigation* scenarios, with increasing emissions up to 2050 but at a slower rate than business-as-usual;
- *Concerted mitigation* scenarios, with decreasing emissions up to 2050.

Under *business-as-usual* scenario, global N₂O emissions increase by 83% between 2005 and 2050. Meanwhile, the actions under the *moderate mitigation* scenarios slow the increase over this period to 26%. The *concerted mitigation* scenarios are 22% lower in 2050 than in 2005. Hence, actions under these scenarios are able to “bend the curve” and reverse the trend of increasing emissions.

The emission reduction potential of N₂O is considerable over the coming years and decades. In 2020, *concerted mitigation* scenarios are 1.8 Tg N₂O-N/yr or around 26% lower than business-as-usual scenarios. In 2050, concerted mitigation scenarios are 5.5 Tg N₂O-N/yr or 57% lower than business-as-usual.

5. What are the benefits of reducing N₂O emissions?

Reducing N₂O emissions will help protect the ozone layer.

One way of gauging the effectiveness of N₂O emission reductions is to estimate the magnitude of avoided emissions over the coming decades in terms of their ability to deplete the ozone layer. If the emissions avoided by the concerted mitigation scenarios are summed up between 2013 and 2050, they amount to an equivalent of 3270 kilotons of ozone depletion potential (ODP Kt) of CFC-11 emissions. This is of comparable magnitude to the ODP Kt estimated to be locked up in the stocks of old refrigerators, air conditioners, insulation foams, and other units (1550-2350 ODP Kt), otherwise referred to as banks⁵. These stocks are considered the most significant remaining source of ozone depleting substances for which action should be taken to accelerate ozone layer recovery.

The rising levels of N₂O are partly undermining the gains in ozone layer recovery being achieved by drawing down

⁵ Banks are stocks of ozone depleting substances that have already been manufactured and used, but not yet released to the atmosphere.

CFCs and other ozone depleting substances. If N₂O emissions continue as a result of anthropogenic sources, ozone layer depletion will also continue. It follows that reducing N₂O emissions will help avoid the continued depletion of the ozone layer and secure the gains of the Montreal Protocol.

Reducing N₂O emissions brings climate benefits.

According to the UNEP Emissions Gap Report 2013, there will be an “emissions gap” of around 8 to 12 Gt CO₂eq in 2020.⁶ This gap has to be closed in order to have a “likely” chance of meeting the internationally agreed-upon target of limiting global warming to two degrees over the long run. Above, it was noted that the potential to reduce N₂O emissions in 2020 is around 1.8 Tg N₂O-N/yr. In units of equivalent CO₂ emissions, this is about 0.8 Gt CO₂eq/yr, which is around 8% of the gap. Hence, drawing down N₂O emissions can make a significant contribution to narrowing the emissions gap.

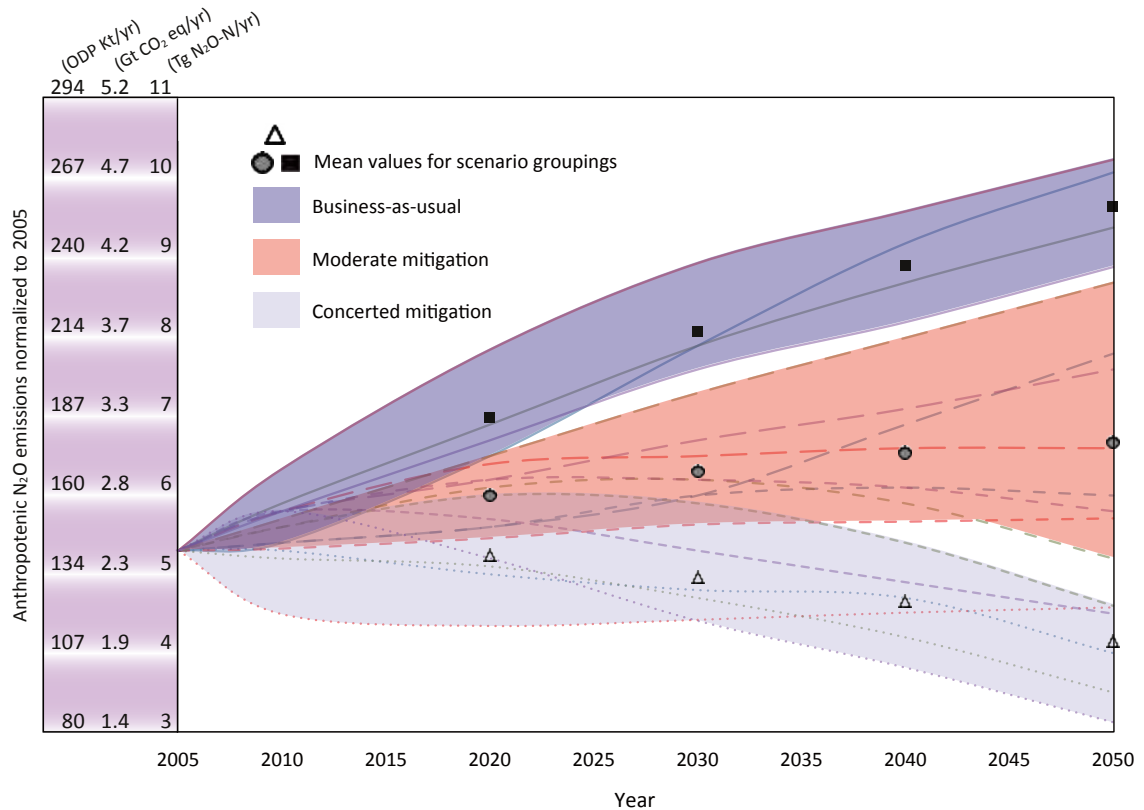
⁶ The ‘emissions gap’ in 2020 is the difference between global emission levels in 2020 consistent with meeting the 2°C target, and levels expected in that year if voluntary country emission reduction pledges are met. The 2°C target (keeping the increase in global average temperature to less than 2°C relative to pre-industrial levels) was agreed upon at the Conference of Parties of the Climate Convention in Cancun in 2010. See UNEP (2013) for details about the emissions gap.

If N₂O emissions continue, they will continue to enhance anthropogenic climate change and their effect will persist for a century or longer even if emissions are reduced in the future.

Apart from protecting the ozone layer and climate, efforts to reduce N₂O emissions will have many other co-benefits, and can help increase wellbeing through the “green economy”.

N₂O emissions are connected to many different aspects of the economy including agriculture, chemical manufacturing, electricity production, transportation, wastewater treatment and fish production. Given these many economic linkages, efforts to reduce N₂O emissions can be seen as part of an effort to build a post-Rio+20 “green economy”. The key idea here is improving “nitrogen use efficiency” across the entire chain of nitrogen flows in the economy, and thereby reducing costs, providing livelihoods, and enhancing the environmental sustainability of agriculture and other sectors. This point of view can help decision makers decide where best to invest their efforts to improve efficiency and lessen nitrogen losses.

Figure ES.2: Projections of anthropogenic N₂O emissions according to the business-as-usual, moderate mitigation, and concerted mitigation scenarios, based on calculations in this report and previous calculations. The mean for each grouping of scenarios are shown by square, circle, and triangle markers, respectively.



Emissions Reduction Potential

	2020	2030	2040	2050
Teragrams (Tg N ₂ O-N/yr)	1.8	3.1	4.2	5.5
CO ₂ equivalent (Gt CO ₂ eq/yr)	0.8	1.5	2.0	2.6
ODP equivalent (Kt/yr)	47	83	113	147

Many co-benefits arise from these efforts, depending on how and where nitrogen efficiency is improved. In agriculture, improving this efficiency could bring increased crop and livestock productivity, reduced requirements for inputs such as nitrogen fertilizer per unit of crop or livestock produced, and lower costs per unit of increasing yield. By raising profits in small-holder farming, it can support on-going livelihoods and help alleviate rural poverty.

Improving nitrogen use efficiency lessens not only the release of N₂O to the atmosphere, but virtually all losses of nitrogen to the environment. This means lower emissions of the air pollutants ammonia and NO_x; less nitrate contamination of groundwater; and less eutrophication of surface waters.

As an illustration of the potential cost savings, an across-the-board improvement of 20% in nitrogen use efficiency was estimated to cost around \$US 12 billion per annum, but would save around US\$ 23 billion in annual fertilizer costs. Furthermore it would bring additional environmental, climate and human benefits worth around \$US 160 billion per annum.

6. How can we overcome barriers to N₂O policies and move forward?

There are various barriers to N₂O mitigation.

Typical barriers include the costs associated with implementing abatement technologies; the need for proper guidance, training and technology transfer on abatement techniques; and the lack of knowledge on how to adapt emission reduction strategies to particular sites and situations. In many cases, the substantial co-benefits of simultaneously reducing N₂O emissions and improving nitrogen use efficiency can provide significant cost savings. However, this will not always be the case.

There are many actions that can help overcome barriers to N₂O mitigation.

Some actions for consideration are:

- Removing subsidies that encourage the overuse or misuse of nitrogen fertilizer and other products, while providing incentives for adopting best management practices that would improve nitrogen use efficiency;
- Putting a price tag on nitrogen pollution through appropriate levies, incentives and tradable permits;
- Encouraging research and development geared towards the development of innovative techniques

to enhance nitrogen use efficiency as well as increased crop and animal productivity in agriculture and other sectors;

- Increasing support for good nutrient management practices in crop and livestock operations through education, extension and outreach, especially to farmers in developing countries;
- Setting clear targets for N₂O emission reductions and for improving nitrogen use efficiency, and putting in place strategies for tracking progress.

The preceding interventions may include a combination of regulatory, financial and voluntary approaches.

There are also many opportunities for embedding N₂O mitigation policies into existing international treaties and institutions.

Since N₂O has global implications for climate change and ozone depletion, there are arguments for acting at the international level against N₂O emissions. Here are some examples of where this could be done:

- **United Nations Framework Convention on Climate Change** – N₂O emissions from nitric and adipic acid production are already being addressed under the Clean Development Mechanism of the Convention, but attention could be given to agriculture and other sectors responsible for the vast majority of N₂O emissions;
- **United Nations Vienna Convention for the Protection of the Ozone Layer** – The Montreal Protocol of the Convention could be expanded to include the control of processes leading to N₂O emissions;
- **United Nations Convention on Biological Diversity** – Targets for reducing N₂O emissions could be linked to the Convention's Aichi Biodiversity Target 8 on nutrient pollution;
- **UNECE Convention on Long Range Transport of Air Pollution** – This UNECE Convention could be expanded to cover controls of N₂O and to include new countries who are a major source of N₂O emissions;
- **Global Program of Action on the Protection of the Marine Environment from Land-based Activities (GPA)** – This intergovernmental process could play a key advisory role in implementing N₂O emission reduction measures building on its existing remit for nutrient management.

Chapter 1

Introduction

A. R. Ravishankara (National Oceanic and Atmospheric Administration, USA), Mark A. Sutton (NERC Centre for Ecology and Hydrology, UK), Eric A. Davidson (Woods Hole Research Center, USA), David Kanter (Princeton University, USA), John S. Daniel (National Oceanic and Atmospheric Administration, USA)

1.1. Background

Nitrous oxide (N_2O) is commonly known as ‘laughing gas’ through its use as an anaesthetic in surgery and dentistry, but it is also naturally present in trace amounts in the Earth’s atmosphere. Interestingly, the Earth is the only planet in the solar system known to contain N_2O in its atmosphere. This is attributed to the presence of life on earth and the cycling of biological nitrogen compounds, which lead to production of N_2O as a by-product.

Almost all N_2O emissions into the Earth’s atmosphere occur unintentionally. Figure 1.1 summarizes the main sources of these emissions. With the exception of specific uses of manufactured N_2O (such as in anaesthesia) and emissions from industrial activity (such as transportation, nylon production, or energy production), all other sources of N_2O emissions are a consequence of the biological nitrogen cycle. In the nitrogen cycle, inert molecular nitrogen (N_2) is transformed into different forms of reactive nitrogen⁷ (N_r) through several natural and anthropogenic processes⁸. The reactive nitrogen is then used as a nutrient for plant and animal growth before eventually returning to an inert form. N_2O is a minor by-product of several of the fundamental processes of the nitrogen cycle where a small fraction of the reactive nitrogen does not return to the atmosphere as N_2 .

Human activities have altered the nitrogen cycle and consequently N_2O emissions⁹. For example, humans have enhanced N_2O emissions from agriculture by increasing the input of reactive nitrogen to these activities through the use of synthetic fertilizers and by cultivating leguminous crops

that fix nitrogen. In the industrial sector, N_2O emissions have increased as an unintended by-product of some manufacturing processes and high temperature burning of fossil fuels.

The anthropogenic and natural emissions of N_2O can be somewhat difficult to separate since human activities also alter natural processes and can either increase or decrease natural emissions. For example, land-use change has decreased the area of natural forests and subsequently decreased N_2O emissions from forest soils, while increased fertilizer use for food production has increased N_2O emissions (see Chapter 3). Overall, human activities have clearly increased N_2O emissions.

It must be noted that natural variations in the Earth System, such as natural climate variability, have altered N_2O emissions over the centuries. However, the scaling up of human activities has been responsible for the substantial observed increase in N_2O emissions since the 19th century (see Chapters 2 and 3). The atmospheric abundance of N_2O in the mid-19th century was around 275 parts per billion (ppb). While this concentration probably reflects some anthropogenic effect from agriculture and fire, these contributions remained small enough to be indistinguishable from the effects of climatic variation on natural N_2O emissions. By comparison, emissions have increased dramatically since the mid-19th century and this increase above the “natural” value can be attributed to human activities, with the dominant source being agriculture. This report uses 275 ppb as the “natural” level of atmospheric N_2O .

A unique characteristic of the nitrogen cycle is the way in which anthropogenic reactive nitrogen compounds switch between chemical forms of nitrogen and contribute to multiple environmental concerns, often called the “nitrogen cascade” (Galloway et al., 2004). Therefore, the growth in anthropogenically-fixed nitrogen has led to an increase in several forms of nitrogen pollution including air, freshwater, marine and land pollution. Of particular importance is the impact of N_2O as a greenhouse gas because it is a strong absorber of infrared radiation given off by the earth’s surface that could otherwise escape to space; and as an ozone depleting substance (ODS) because it degrades to nitrogen

7 Reactive nitrogen refers to any chemical form of nitrogen other than dinitrogen (N_2). Reactive nitrogen (N_r) compounds include NH_3 , NO_x , N_2O , NO_3^- and many other chemical forms, and are involved in a wide range of chemical, biological and physical processes.

8 The key processes include *nitrogen fixation*, the process by which inert nitrogen in the atmosphere is converted into ammonia (NH_3). This can occur naturally or synthetically; *nitrification*, the biological transformation of ammonium into nitrate; *denitrification*, the biological conversion of nitrate into molecular nitrogen; *mineralization*, the biological conversion of nitrogen in plant or animal remains or waste to ammonium by microorganisms; *anammox*, the biological conversion of ammonium and nitrite into molecular nitrogen; and *chemo-denitrification*, denitrification through abiotic (chemical rather than biological) reactions.

9 Humans began to influence the natural nitrogen cycle in the pre-industrial era as they expanded agricultural land, used fire as a land clearing and management tool, and cultivated leguminous crops that carry out biological nitrogen fixation.

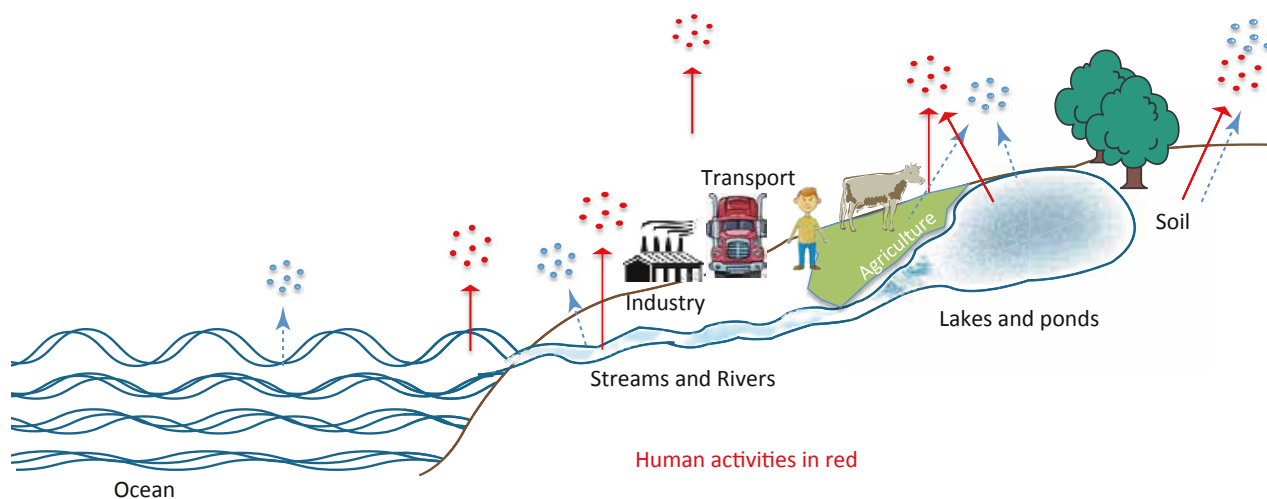


Figure 1.1: Various sources of N₂O emissions to the atmosphere. Blue broken arrows represent natural emission sources while red solid arrows represent emission sources influenced by human's activities. Humans have enhanced N₂O emissions directly through activities such as agriculture and industrialization, and have also done so indirectly through the perturbation of the Earth's System including its soils, forests, lakes/ponds, streams/rivers, and oceans. Consequently, attributing emissions to human activities is often a challenge.

oxides in the stratosphere where they catalytically destroy the ozone layer. It should be noted however that although this report focuses on N₂O and its impact on climate and the ozone layer, the influence of human activities on other nitrogen-related environmental issues should be kept in mind.

With a lifetime of more than a hundred years¹⁰, N₂O is similar to CO₂ (as a greenhouse gas) and some of the CFCs (as an ozone layer depleting gas) but different from methane. The long persistence of N₂O in the atmosphere means that most of the N₂O emitted by humans over the last century is still in the atmosphere and that its effect on climate change and ozone layer depletion will persist even if emissions were to stop immediately (See Chapter 2).

Considering the importance of N₂O on climate change and ozone depletion, it could be argued that not enough attention has been given to reducing its emissions. For example, although the "Vienna Convention for the Protection of the Ozone Layer" mentions N₂O as an ozone-depleting substance, it is not regulated under the "Montreal Protocol on Substances that Deplete the Ozone Layer". Furthermore, a review of approved projects of the Global Environment Facility (GEF) suggests that very few of the 1,091 projects (as of 2013) that fall under the category of climate change and ozone depleting substances specifically target N₂O. Furthermore, the Clean Development Mechanism (CDM) of the UNFCCC up to now has only focused on the industrial sector of N₂O emissions, which together with fossil fuel combustion sources, only accounts for around 15% of total gross anthropogenic emissions. Within the industry sector, progress has been made in reducing emissions from adipic acid plants but policymakers have barely begun to address the other important industrial source of N₂O emissions – nitric acid plants. So, while some action has been taken on N₂O, much more could be done to reduce its emissions and increase the protection of climate and the ozone layer.

¹⁰ The persistence in the atmosphere, technically referred to as the "lifetime", is a metric used to gauge how long an emitted chemical stays in the atmosphere. It is defined as the time it takes for approximately 63% (time constant for an exponential removal of a chemical) of the emission to be removed from the atmosphere. For N₂O this time constant is around 120 years and is not expected to be substantially changed with climate change. In this report, the lifetime of N₂O is taken to be 120 years for all calculations.

1.2. Objective of Report

With the above concerns in mind, this report aims to inform policymakers and stakeholders about the impacts of N₂O emissions on the climate and ozone layer and opportunities for reducing its emissions.

The report is divided into two parts:

- **Part I** lays out the environmental issues associated with N₂O emissions, especially its influence on climate and ozone layer depletion (Chapter 2). It also highlights the various natural and anthropogenic sources of N₂O and presents future projections of N₂O concentration in the atmosphere (Chapter 3).
- **Part II** describes the main mechanisms leading to N₂O emissions and presents options for reducing emissions. It also provides estimates of the emission reduction potential from various sectors. This information is provided for agriculture (Chapter 4), industry and fossil fuel combustion (Chapter 5), biomass burning (Chapter 6), and wastewater and aquaculture (Chapter 7). Chapter 8 presents emission projections based on the mitigation potentials presented in earlier chapters. It also articulates how reducing emissions is closely linked to the concept of "green economy" and ends with a description of international policy settings applicable to N₂O emissions reduction.

An underlying premise of the report is that actions to reduce N₂O emissions and protect climate and the ozone layer can also help solve other environmental problems associated with excess flows of nitrogen. Abating the sources of N₂O emissions is likely to reduce nitrate contamination of groundwater, abate emissions of ammonia and other nitrogen air pollutants and therefore lower deposition of nitrogen, and reduce the loading of nitrogen to lakes, rivers, and coastal zones and therefore decrease the occurrence of eutrophication of surface waters (Galloway et al., 2008; Gruber and Galloway, 2008; Oenema et al., 2011; Sutton et al., 2013). Solving these problems would mean better environmental quality and reduced threats from nitrogen pollution to both human health and biodiversity.



Copyright: Shutterstock, Image # 77605879

Part 1

The Nitrous Oxide Challenge

Chapter 2

N₂O: Its Role in Climate Change and Ozone Layer Depletion

Lead Authors: John S. Daniel (National Oceanic and Atmospheric Administration, USA), Elisabeth Holland (University of the South Pacific, Fiji), A. R. Ravishankara (National Oceanic and Atmospheric Administration, USA)

Contributing Authors: Kristie Boering (University of California, USA), Priya Sharma (University of the South Pacific, Fiji)

Chapter 1 of this report provides a brief discussion of N₂O emissions, their relationship with the nitrogen cycle, and how the alteration of nitrogen cycle processes by humans has led to increased N₂O emissions. This chapter describes in more detail the accumulation of N₂O in the atmosphere and its impact on climate change and depletion of the ozone layer.

2.1. Increasing concentration of N₂O in the atmosphere

Nitrous oxide (N₂O) has been in the atmosphere for as long as there has been life on Earth (Wayne, 2000). Up until the last one or two centuries, its concentration did not change appreciably over thousands of years (Figure 2.1, left panel). This is because the rate of “natural” emissions to the atmosphere was roughly equal to their removal rate

from the atmosphere by natural processes (Joos and Spahni, 2008).

As seen from ice core and firn records, N₂O began to increase slightly after 1700 AD (Figure 2.1, middle panel). Its atmospheric abundance increased more rapidly from around 1850 and very rapidly from 1950 (Figure 2.1, right panel). This followed the rapid increase in application of fertilizer, made possible by the invention in the early 20th century of the Haber-Bosch process¹¹ used in the synthesis of nitrogen fertilizer. Atmospheric measurements show that N₂O concentration has increased by more than 0.2% per year over the past few decades; this is consistent with approximately 1% increase per year in anthropogenic emissions.

¹¹ The Haber-Bosch process has allowed humans to transform inert dinitrogen gas into ammonia (NH₃) and subsequently synthetic fertilizer.

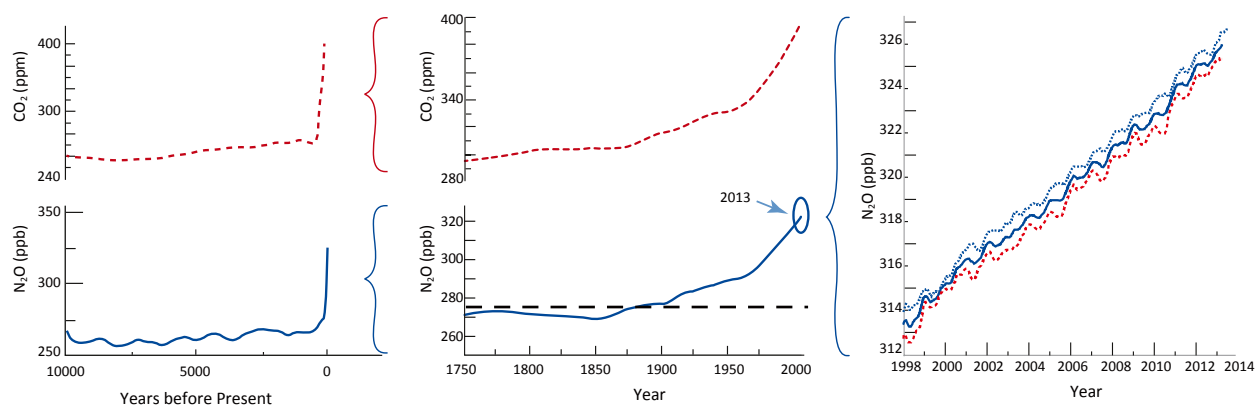


Figure 2.1: Past and present concentration of nitrous oxide in the atmosphere. **Left hand panel.** Plots of N₂O, and CO₂ from ice cores going back 10,000 years supplemented with in-situ atmospheric data for the past few decades. Adapted from Joos and Spahni, (2008). **Middle panel.** Atmospheric abundances of CO₂ and N₂O from ice core and firn air (air trapped in compacted snow) from 1750. The 1750 to 2010 data are again a composite with in-situ data for the last few decades. Adapted from MacFarling Meure et al (2006). **Right panel.** Measurements carried out over the globe (courtesy of NOAA/ESRL/GMD) since 1998. The atmospheric abundance of N₂O over the northern hemisphere (broken blue line) is slightly (but clearly) larger than that of the southern hemisphere (broken red line). This hemispheric difference is consistent with larger human-influenced emissions in the northern hemisphere. The global average is shown as a solid line.

Both CO₂ and N₂O in the atmosphere have natural and human-influenced sources¹² (see Chapter 3), with human activities responsible for increasing concentrations shown in the middle and right-hand panels of Figure 2.1. The increase in atmospheric concentrations of both gases parallels the increase in global population and industrialization experienced since around the middle of the 19th century. Today, the “natural” emissions of N₂O are still larger than human-influenced emissions. However, as noted earlier, natural emissions are not thought to have changed significantly and do not lead to an increase of N₂O in the atmosphere. Anthropogenic emissions, on the other hand, are becoming more and more significant¹³ and are increasing the levels of N₂O in the atmosphere. Anthropogenic emissions are currently more than 40% of natural emissions and human activities have enhanced atmospheric concentration levels by almost 20% relative to “natural” levels.

As stated in Chapter 1, the global nitrogen cycle has been altered since the significant expansion of agriculture and industry. This includes a large increase in nitrogen fixation (Galloway et al., 2004) due to agricultural practices and a 3- to 5-fold increase in nitrogen deposition in industrialized regions of the world (Lamarque et al., 2005; Denman et al., 2007) due to increased industrial activities. The two processes (nitrogen fixation and nitrogen deposition) contribute to the enhancement of N₂O emissions (Butterbach-Bahl et al., 2011; Pinder et al. 2012).

Studies using nitrogen and oxygen isotopes (Park et al., 2012; Roeckmann et al., 2003) have helped identify the sources of rising levels of N₂O. Measurements of air samples from Cape Grim, Tasmania, dating back to 1978, combined with data from Antarctica firn air dating back to 1940 (Park et al., 2012), show that the isotopic composition of N₂O has changed. The observed changes in isotopes are consistent with an increase of N₂O from fertilized agricultural fields, and therefore provide further evidence that the N₂O build-up is mostly related to increasing fertilizer use¹⁴.

2.2. Role of N₂O in climate change and ozone layer depletion

Increasing concentrations of N₂O in the atmosphere have significant implications for efforts to mitigate climate change and prevent the depletion of the ozone layer.

- 12 “Natural” emissions of N₂O are referred to as those that would have occurred in the absence of significant human activity while “human-influenced” emissions (or “anthropogenic” emissions) refer to direct emissions caused by human activities, as well as net increases in emissions from natural sources caused by the alteration of natural processes due to human activities.
- 13 The background atmospheric concentration level of N₂O (attributed to natural emissions) is assumed to be 275 parts per billion (ppb) (see Chapter 1).
- 14 When nitrogen substrate is plentiful, as in a fertilized agricultural field, microbes readily discriminate against nitrogen-15, producing N₂O that has a lower nitrogen-15 to nitrogen-14 ratio relative to when nitrogen substrate is limited. Measurements of isotopic changes in nitrogen, along with the changes in isotopes of oxygen that are not sensitive to the amount of reactive nitrogen fertilizer, clearly show that the recent increase in atmospheric N₂O is due to fertilization of the soil.

2.2.1. N₂O is a greenhouse gas. Human-influenced N₂O is the third largest well-mixed¹⁵ climate-forcing agent today.

Nitrous oxide is a powerful greenhouse gas since it very efficiently absorbs energy at infrared wavelengths, meaning that it effectively absorbs infrared radiation emitted by the Earth’s surface and lower parts of the atmosphere. The absorption capability (and thus warming capacity) of a molecule of N₂O is roughly three hundred times larger than that of a molecule of CO₂ when summed up over 100 years¹⁶. This largely makes up for its more than two thousand times lower atmospheric concentrations relative to CO₂. Currently, anthropogenic N₂O’s contribution to radiative forcing¹⁷ is nearly 10% of that due to CO₂, making it the third largest well-mixed climate forcing agent today. While the forcing by CH₄ has not increased significantly over the past decade (because its atmospheric growth rate has significantly decreased during that time), the forcing due to N₂O continues to increase with a similar fractional rate as that of CO₂.

The radiative forcing by CO₂, CH₄, and N₂O currently contributes more than 85% of the total forcing from well-mixed greenhouse gases. There are other chemicals, for example HFCs, that could contribute significantly in the future, but at the same time, some currently large contributors, such as CFCs, are declining due to global action on their production and consumption. Hence it is particularly significant that N₂O atmospheric concentration is steadily increasing.

To provide a context for N₂O’s importance to climate, it is useful to compare its contribution to radiative forcing with that of hydrofluorocarbons (HFCs), whose mitigation is being actively discussed in policy circles¹⁸. Figure 2.2 compares their contributions in the recent past and those projected in the future. The growth in forcing from 1990 to 2010 and in the future is apparent for both classes of gases. The values in the figure for 2030 and 2050 for N₂O show the potential for substantial increases in N₂O forcing in the coming decades, comparable to that of HFCs if emissions continue to grow unabated. Therefore, analogous to HFCs, reducing N₂O

15 “Well-mixed” is a term used for gases that have lifetimes long enough to be relatively homogeneously mixed in lower part of the atmosphere. Hence, their impact on climate and ozone depletion does not depend on where in the atmosphere they are emitted. Measurements of such a gas in one remote surface location will be almost identical to measurements in any other remote location. It should be noted that well-mixed gases may still demonstrate concentration variations in non-remote locations, particularly right next to large source or sink regions.

16 An emitted molecule of N₂O is about 300 times more potent than an emitted molecule of CO₂ for a 100-year time horizon when the Global Warming Potential (GWP) (which takes into account the atmospheric lifetime) is used as a metric (GWP-100 yr for N₂O = 300). The GWP is a ratio of the integrated radiative forcing from a pulse of a unit mass of a given well-mixed greenhouse gas as compared to that from the pulse of a unit mass of CO₂, and is thus a unitless quantity. The time horizon, typically chosen to be 100 years (referred to as GWP-100 yr in the previous sentence), is the time over which the forcing is integrated. GWP values thus represent a measure of the relative impact on climate among greenhouse gases over that time horizon. The choice of the time horizon is more of a policy decision than a scientific one.

17 Radiative forcing is a measure of how a climate forcing agent influences the Earth’s energy balance, with a positive value indicating a net heat gain to the lower atmosphere, which leads to an increase in global average surface temperature (warming) and a negative value indicating a decrease in heat gain (cooling).

18 See, for example, UNEP. 2011. HFCs: A Critical Link in Protecting Climate and the Ozone Layer. United Nations Environment Programme (UNEP), Kenya.

emissions would help in mitigating the future total climate forcing.

2.2.2. N₂O is also an “ozone depleting gas”. N₂O emissions are currently the most significant ozone-depleting emission.

The ozone layer in the stratosphere, as has been well established, protects humans and the biological world from harmful ultraviolet radiation from the sun. Depletion of the ozone layer has been mostly attributed to human-related emissions of halogenated (chlorine- and bromine-containing) chemicals. Amongst these, manmade chlorofluorocarbons (CFCs) and brominated chemicals such as halons and methyl bromide are the major contributors.

The Montreal Protocol on Substances that Deplete the Ozone Layer, a protocol of the Vienna Convention, regulates a wide variety of chemicals that deplete the ozone layer, but N₂O is *not* among the substances it controls. Nevertheless, N₂O is the source of nitrogen oxides (NO_x) in the stratosphere, which efficiently destroy ozone in a manner similar to that of chlorine and bromine chemicals (see Box 2.1). The role played by NO_x in ozone depletion was identified even before the role of CFCs and halons was known. In fact, the earliest concerns about ozone layer destruction came about because of the threat posed by NO_x emitted by supersonic aircraft flying in the stratosphere (Johnston, 1971; Crutzen, 1970).

To compare the importance of different substances in depleting stratospheric ozone, a metric called the “Ozone Depletion Potential” (ODP)¹⁹ is used. Although not listed in the Montreal Protocol Annexes, anthropogenic N₂O could also be considered an ozone-depleting substance (ODS) if it were evaluated using the same criteria as that used for the selection of currently controlled ODSs. The ODP of N₂O has been calculated to be about 0.017 (Ravishankara, et al., 2009), which is comparable to the ODPs of Montreal Protocol-controlled chemicals such as HCFC-123 (0.02), HCFC-124 (0.022), HCFC-225ca (0.025), and HCFC-225cb (0.033).

More importantly, when the current emissions of ozone-depleting substances are weighted by their ozone-depleting potential, N₂O emissions are currently the most important ozone-depleting emission (Figure 2.3). Indeed, it was already the fourth most important type of emission in 1987 when the Montreal Protocol was adopted. Undoubtedly, N₂O has only become important because CFCs and other ozone-depleting substances have been drastically reduced through the Montreal Protocol. The contributions of CFCs and halons to ozone depletion continue to decrease and are projected to continue doing so, while the contribution of N₂O to ozone-layer depletion is rising now and will continue to do so in the future under business-as-usual conditions as shown in Figure 2.3. Therefore, N₂O is expected to remain the dominant ozone-layer-depleting emission.

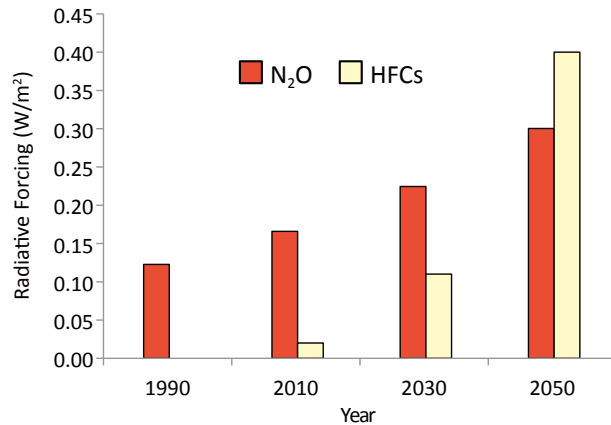


Figure 2.2: Contributions of N₂O and HFCs to radiative forcing at different times in the recent past and the future. Historical forcing is based on observed atmospheric concentrations. Future projections of N₂O are taken from the high RCP scenario (RCP8.5). The HFC projected forcing is taken from the “upper range” projection in the UNEP HFC Report (UNEP, 2011).

Beyond 2050 anthropogenic N₂O emissions have a bigger impact on ozone layer depletion than the sum of all other substances considered under the Montreal Protocol (Figure 2.3, right panel). Even during the next few decades, the contribution of N₂O emissions are greater than any of the other individual measures available to reduce ODS emissions.

On the other hand, there are a number of factors that may lessen the impact of N₂O on the ozone layer (Ravishankara et al., 2009, Portmann et al., 2012). These include the presence of CH₄, the presence of aerosols from volcanoes, and the influence of stratospheric cooling caused by increased CO₂, all of which influence the relative effectiveness of ozone destruction by halogens, chlorine and nitrogen oxides. Even so, these factors are secondary to the direct impact of N₂O and do not change the main conclusion that N₂O currently has a significant effect on the ozone layer and this is expected to grow unless action is taken to reduce N₂O emissions (Portmann et al., 2012).

2.2.3. N₂O has a long atmospheric lifetime and this has important implications.

Nitrous oxide is essentially inert in the lower part of the atmosphere, the troposphere. Its loss occurs higher in the atmosphere, with the majority of it taking place in the stratosphere. Furthermore, unlike CO₂, in which a significant fraction, between 45 and 55%, of gas emitted into the atmosphere is sequestered within two decades by the biosphere or ocean mixed layer (Joos et al., 2013; Ballantyne et al., 2012), N₂O is not significantly removed by dissolution into the oceans. As a result, N₂O has a long atmospheric lifetime currently estimated to be approximately 120 years (See Chapter 1), and has almost the same concentration at all surface locations.

The long atmospheric lifetime has significant implications (Ravishankara and Lovejoy, 1994). Firstly, emitted N₂O accumulates in the atmosphere for many decades, implying that most of the natural and human induced N₂O emissions over the past 50 years are still in the atmosphere today. Secondly, even if its emissions were stopped immediately, it would take several centuries for N₂O to be removed from

¹⁹ ODP is defined in different ways, but the common metric used in the Montreal Protocol is referred to as the steady-state ODP. This ODP is defined as the ratio of ozone-layer depletion by the continued emission of one kilogramme of a substance relative to that by the continuous emission of one kilogramme of CFC-11 when both reach steady state, i.e., when their atmospheric abundances no longer demonstrate any long-term changes due to those emissions. Because it is a ratio of ozone depletion amounts, it is a unit-less quantity.

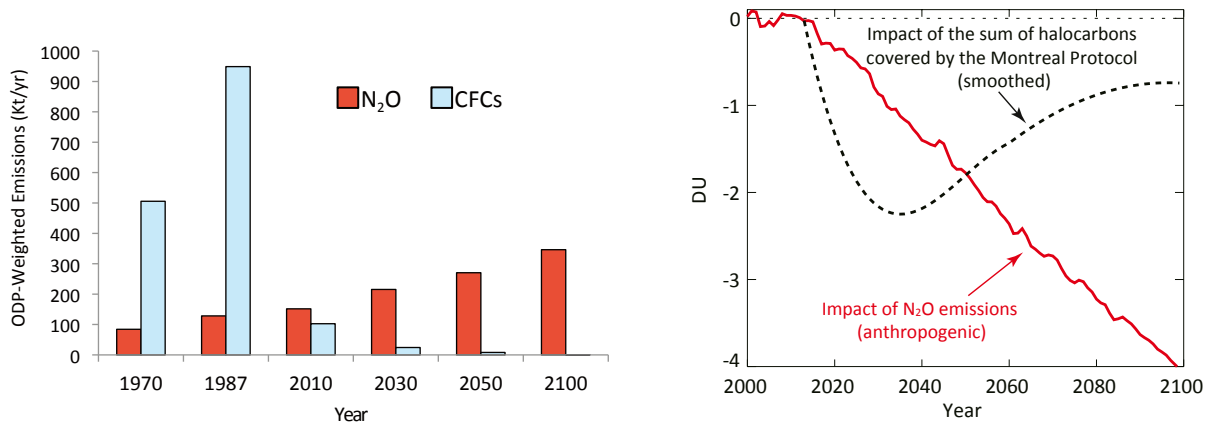


Figure 2.3. Left panel: ODP-weighted emissions of anthropogenic N₂O and the sum of emissions of CFC-11, CFC-12, and CFC-13 for 6 different years. Included is 1987, the year around which CFC emissions peaked and the Montreal Protocol was signed. Future N₂O emissions are calculated from concentration projections of the highest future RCP forcing scenario (RCP8.5) (see chapter 3); CFC projections are taken from the A1 scenario of WMO (2011). **Right panel:** Impact on global ozone from future emissions of N₂O and the sum of halocarbons covered by the Montreal Protocol (adapted from Daniel et al., 2010). This means that eliminating N₂O emissions after 2010 would lead to a 4 DU²⁰ ozone increase by 2100 as compared with a less than 1 DU increase if all long-lived halocarbon emissions are eliminated in 2010²¹.

20 DU (Dobson Unit) is a common unit used to measure overhead column ozone amounts. One DU is the number of molecules of ozone that would be required to create a layer of pure ozone 0.01 millimeters thick at a temperature of 0 degrees Celsius and a pressure of 1 atmosphere (the air pressure at the surface of the Earth).

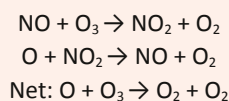
21 The smaller impact of the halocarbons is due to the fact that their emissions are already scheduled for elimination under the Montreal Protocol. For reference, the column amount of ozone is roughly 300 DU.

BOX 2.1: Nitrous oxide and the depletion of the stratospheric ozone layer (WMO, 2011)

Forty years ago, projections of enhanced emissions of reactive nitrogen oxides (NO_x) due to potential increases in stratospheric supersonic aircraft activity led to the earliest concern (circa 1971) about ozone layer depletion. Later, from around 1974, attention shifted to manmade CFCs and Halons. Those concerns and the discovery of the ozone hole led to the Montreal Protocol. Now, there is concern about the increasing concentrations of N₂O that would, if unabated, continue to deplete the ozone layer in the future.

Ozone is produced in the stratosphere via the splitting of O₂ by light (photolysis) to give oxygen atoms, followed by the reaction of O atoms with molecular O₂. This process is balanced by the reaction of O atoms with O₃ to destroy ozone. In addition to the O atom reaction with ozone, there are catalytic reactions involving chlorine, bromine, hydrogen, and nitrogen radicals that contribute significantly to ozone destruction. These chemical processes along with O₃ production processes and transport account for the distribution of ozone in the stratosphere.

The sequence of reactions that destroys ozone via nitrogen oxides (NO_x = NO + NO₂) are:



Gas phase catalytic reactions of NO_x through the above catalytic cycle, like those involving chlorine atoms, bromine atoms, or OH/HO₂ radicals, can destroy millions of ozone molecules before NO_x is removed from the stratosphere. Thus a small amount of NO_x can cause a large depletion in ozone abundance, as was discovered and quantified in the early 1970s.

N₂O is transported to the stratosphere where it is degraded by light to inert nitrogen and oxygen as well as via reactions with highly energetic oxygen atoms; the latter process leads to NO_x production and makes N₂O the primary source of NO_x in the stratosphere. Roughly 10% of destroyed N₂O is converted to NO. The nitrogen oxides from natural N₂O have been a part of the catalytic cycles that have contributed to the natural levels of stratospheric ozone over the past centuries. The same is true for chlorine and bromine atoms from naturally occurring chemicals such as methyl chloride and methyl bromide from the oceans. But now that N₂O is increasing due to anthropogenic emissions, it is leading to a higher-than-natural degree of ozone depletion.

the atmosphere. In other words, just like CO₂ and CFC-12, a quick reduction in the atmospheric concentration of N₂O is not possible even if rapid policy decisions were to lead to instant reductions in emissions. This is the reason why CFCs are still persisting and destroying the ozone layer today even though their emissions have been reduced to less than 10% of what they were during the 1980s, when they were near their peak. Thirdly, because of its long lifetime, N₂O is well-mixed in the lower atmosphere. This uniform mixing, coupled with the diffuse nature of the N₂O emission sources, makes it challenging to identify the individual sources of N₂O via atmospheric observations. Hence, bottom-up (see section 3.2 and 3.3 for further explanation) inventory estimates are required to attribute N₂O emissions by source and sector.

2.3. Continuing N₂O emissions: implication for climate and the ozone layer

Unlike the CFCs, N₂O emissions and concentrations will continue to increase in the future under most current projections. These continued increases will lead to additional ozone depletion and will contribute to the warming of the climate system. Although the abundance of CFCs has begun to fall and are projected to continue to decline, leading to an ozone increase, the presence of anthropogenic N₂O emissions will lead to more ozone layer depletion compared to what would have occurred in the absence of such emissions. Therefore N₂O is somewhat counteracting the benefits gained by the Montreal Protocol

Figure 2.3 shows that ODP-weighted emissions of N₂O are greater than those of CFCs in 2010. The GWP-weighted

emissions of N₂O are also larger than those of CFC emissions in 2010. Indeed, the majority of future projections suggest that N₂O will increasingly affect stratospheric ozone and warm climate. But Figure 2.3 also shows that even in 2100 N₂O is not expected to have the impact on ozone depletion that CFCs had in the 1980s.

2.4. Conclusions

- Nitrous oxide is the third most important anthropogenic well-mixed greenhouse gas today and is currently the most important ozone depleting substance emission to the atmosphere.
- Observations show that human activities have increased the atmospheric concentration of N₂O by about 20% relative to its natural level, which had been roughly constant over ten thousand years. Currently, anthropogenic emissions are already more than 40% of the natural emissions. The anthropogenic emissions could equal those from natural sources towards the end of the 21st century if emissions continue to increase unabated.
- Atmospheric observations are consistent with agriculture being the largest contributor to human influenced emissions of N₂O.
- The dual benefits to the Earth System of reducing N₂O emissions are clear, both in terms of protecting the ozone layer and reducing climate forcing in the future. The extent to which these benefits can be achieved requires, among other things, clear knowledge of the emissions of N₂O from different sources and reconciliation of the N₂O budget.

Chapter 3

N₂O: Sources, Inventories, Projections

Lead Authors: Eric Davidson (Woods Hole Research Center, USA), David Kanter (Princeton University, USA)

Contributing Authors: Emma Suddick (Woods Hole Research Center, USA), Parvatha Suntharalingam (University of East Anglia, UK)

3.1. Introduction

Chapter 1 of this report described how human activities have disrupted the natural nitrogen cycle and the consequent increase in N₂O emissions, while Chapter 2 highlighted the role of N₂O in climate change and ozone layer depletion. This chapter provides estimates of N₂O emissions from its various natural and anthropogenic sources, partitioning them into different economic sectors, and outlining the inherent uncertainties in these estimates. The chapter then summarizes published scenarios and projections for future emissions and resulting atmospheric N₂O concentrations through 2050.

3.2. Natural emissions

3.2.1. Approaches for estimating natural N₂O emissions.

Two approaches can be used to estimate natural N₂O emissions – “bottom-up” or “top-down”. The “bottom-up” approach sums up emission inventories from field measurements organized according to ecosystem type and/or by geographic region. The “top-down” approach estimates global N₂O emission from averages of atmospheric mixing ratios²² measured in ice cores prior to the industrial revolution and estimates of the lifetime of N₂O in the atmosphere, assuming that atmospheric concentrations were at an approximate steady state at that time.

3.2.2. Estimation of natural emissions.

Using the “bottom-up” approach, estimates of current natural emissions of N₂O from terrestrial, marine and atmospheric sources based on several inventories range from 10.2 to 12.0 Tg N₂O-N/yr (Mosier et al., 1998; Galloway et al., 2004; IPCC, 2007; Crutzen et al., 2008; Syakila and Kroeze, 2011). The IPCC fourth assessment report (AR4) estimated that current natural sources of N₂O add up to roughly 11.0 Tg N₂O-N/yr, which is the sum of emissions from terrestrial

(6.6 ± 3.3), marine (3.8 ± 2.0) and atmospheric sources (0.6; range: 0.3 to 1.2) – see Figure 3.1. The indicated uncertainty ranges come from the range of bottom-up estimates. Studies published after AR4 suggest that these uncertainties may be even larger than those given in AR4. For example, recent estimates of the oceanic source include values up to 6.2 Tg N₂O-N/yr (Bianchi et al., 2012; Suntharalingam et al., 2012), which would extend the uncertainty range of both oceanic and total N₂O emissions.

Using the “top-down” approach, with an assumed atmospheric lifetime of N₂O of 120 years²³ (Chapter 2), pre-industrial emissions are estimated to be about 11.1 Tg N₂O-N/yr. It should be noted that this estimate is uncertain because of the lack of complete understanding about the influence of anthropogenic changes prior to the industrial revolution (such as the expansion of agriculture) and variability of natural emissions.

Between 1730 and 1850 N₂O concentrations in the atmosphere varied slightly from year to year and decade to decade, but showed little or no consistent long term trend (see Chapter 2 and Machida et al., 1995). Although Syakila and Kroeze (2011) estimated that average net anthropogenic emissions were around 0.5 Tg N₂O-N/yr during the 18th and early 19th centuries, these emissions were so low that their signal cannot be distinguished from the effects of natural climatic variation.

Despite the large uncertainties of both bottom-up inventories and top-down modelling based on atmospheric N₂O, there is general agreement that natural emissions were and probably still are between 10 and 12 Tg N₂O-N/yr. These natural emissions are not contributing to the increase of N₂O in the atmosphere because they are balanced by an equal amount of sinks, primarily natural chemical breakdown of N₂O in the stratosphere, which has developed over a long period of time. Meanwhile, anthropogenic emissions are accumulating in the atmosphere and increasing the atmospheric concentration of N₂O because they are not balanced by sinks. However the stratospheric sink should

²² The “mixing ratio” is a metric commonly used in the atmospheric sciences to indicate the concentration of a trace gas in air. It is defined as the number of moles of a trace gas such as N₂O per number of moles of air. In the atmosphere, this is also equivalent to the volume of a trace gas per volume of air. It is typically expressed in units of parts per billion (ppb) or parts per million (ppm).

²³ Estimates of atmospheric lifetimes of N₂O range from around 110 to 130 years. This is among several sources of uncertainty in top-down modeling of constraints on N₂O emissions. Based on only this range of uncertainty in the lifetime, then the pre-industrial source estimate would range from 10.2 to 12.1 Tg N₂O-N/yr.

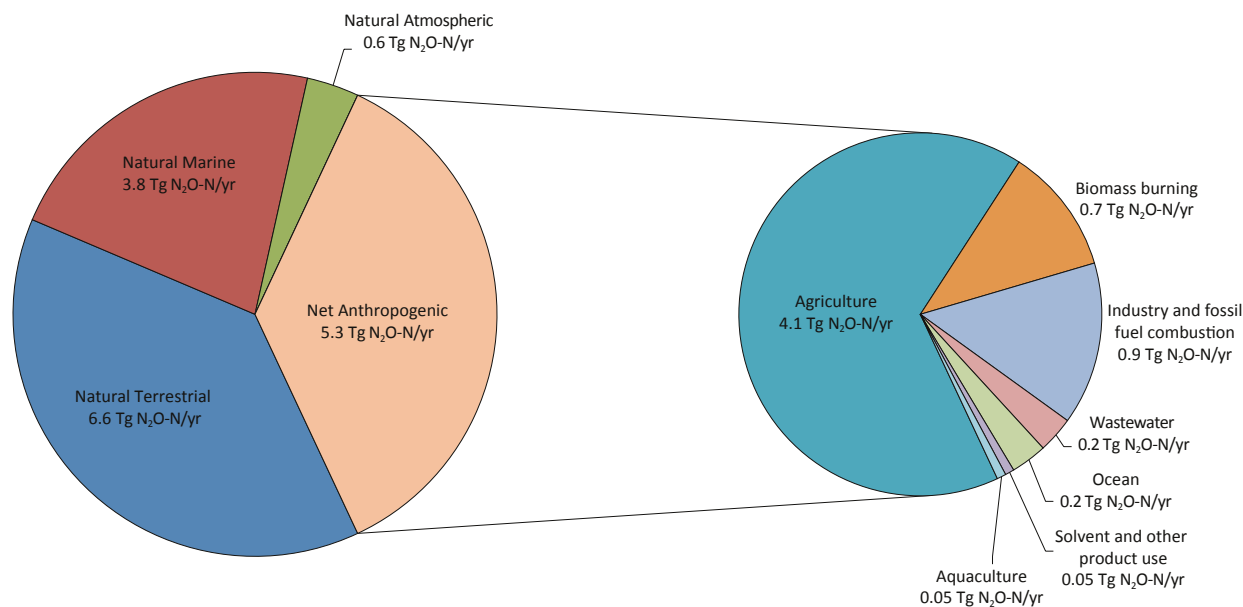


Figure 3.1: Natural vs. anthropogenic N₂O emissions in 2005. The values for natural emissions (terrestrial, marine, and atmospheric sources in the pie chart on the left) are taken from Denman et al. (2007), while the anthropogenic values are the best estimate values from this report’s syntheses in Chapters 4-7, as summarized in Table 3.1. The left pie chart takes into account the effect of land use changes on reducing net anthropogenic emissions (about 0.9 Tg N₂O-N/yr). As noted in the text, natural emissions are not contributing to the increase of N₂O in the atmosphere because they are balanced by an equal amount of sinks.

eventually come into a new equilibrium after emissions stop growing, and atmospheric concentrations will then stabilize at a much higher concentration than currently.

3.3 Anthropogenic emissions

3.3.1. Top-down atmospheric modelling constraints

Modern anthropogenic emissions of N₂O can be calculated using the same top-down method described above. In this case, the change in atmospheric concentrations from 1850 to the present is assumed to be entirely from anthropogenic sources, assuming relative stability of natural emissions over the same period and the same atmospheric N₂O lifetime of 120 (±10) years (Prather et al., 2001). The atmospheric concentrations were averaged for the period 2000-2007 to avoid artefacts of interannual variation, yielding an estimate for net anthropogenic emissions of 5.3 Tg N₂O-N/yr (range 5.2–5.5) for that period. This estimate includes a decrease in emissions from forest soils because of deforestation, and an increase in emissions from expanded activity in agriculture and other sectors.

3.3.2. Bottom-up inventory estimates

A protocol has been developed by the IPCC (2006) for use by countries to estimate their N₂O emissions using driving force data and emission factors. The most basic IPCC approach (“Tier 1 Protocol”) to calculate N₂O emissions is to multiply “activity” data from agriculture, energy generation, transportation, and other sectors by emission factors (EFs). “Activity” data are indicators of the level of activity in the sector and “emission factors” give the amount of N₂O emitted per unit of activity. They are averages across a broad range of conditions and often do not yield accurate estimates for individual sites. Nevertheless, there is evidence that errors on the small scale are largely cancelled when aggregated to larger scales (Del Grosso et al., 2008).

Countries that have sufficient data to calculate EFs more specific to their particular situations are allowed to use them under IPCC’s “Tier 2 Protocol”, which presumably yields more accurate estimates for those specific regions and management practices than those calculated under the “Tier 1 Protocol”. Under the “Tier 3 Protocol”, countries with access to validated biogeochemical models (and sufficient input data) are allowed to use these models to calculate N₂O. This presumably yields even more accurate estimates if the models skilfully account for the spatial and temporal variation of the most important factors affecting emissions.

With the advent of new laser technologies for measurements of N₂O fluxes, there is likely to be continued improvement in estimating emission factors for the “Tier 1 and Tier 2 Protocols” and for validating the biogeochemical models used with the “Tier 3 Protocol”. However, it will remain difficult to fully account for the large spatial and temporal variation of N₂O emissions. Improvement in the quality of activity data for each country, such as its fertilizer application rates, livestock production, and manure handling procedures, is also necessary for improved emission estimates. Another source of inaccuracy in the use of EFs is that they assume a linear relationship between nitrogen application rates and N₂O emissions, which is not necessarily the case (see Chapter 4).

Table 3.1 shows the most recent and comprehensive efforts at estimating anthropogenic emissions from bottom-up inventories and from combinations of integrated bottom-up and top-down analyses. The column labeled “This Report” sums the estimates from other chapters to derive a “best estimate” for total net anthropogenic N₂O emissions of 5.3 Tg N₂O-N/yr, which is equal to the top-down estimate (section 3.3.1). The best estimate from this report is lower than the estimates from other inventories shown in Table 3.1, partly because of lower updated estimates in chapters 4-7 and partly because this report’s inventory includes the effect of lower emissions of N₂O from tropical forest soils due

Table 3.1. Published inventories of anthropogenic N₂O emissions and the “best estimates” from this report.
All units in Tg N₂O-N per year

	FAO ¹	EDGAR ²	USEPA 2012 ¹	Syakila & Kroeze 2011 ³	Davidson 2009 ⁴	Del Grosso et al., 2008 ⁵	Crutzen et al., 2008 ⁶	IPCC AR4 2007 ⁷	Mosier et al., 1998 ⁸	This Report ⁹	Estimate range
Agriculture	4.1	3.8	4.6	5.1	5	4.9	4.3 - 5.8	5.1	6.8	4.1⁽¹⁰⁾	3.8-6.8
Fertilizer	1.4										
Direct	1.1				2.2						
Indirect	0.3	3.6		2.3					3.9		
Manure	1.8				2.8	4.5					
Direct	1.4		4.2								
Indirect	0.4										
Organic Soils	0.2			0.1					0.1		
Crop Residues	0.3			0.3					0.4		
Crop Biological Nitrogen Fixation (C - BNF)				0.1					0.1		
Manure Management	0.3	0.2	0.4	2.3		0.4			2.3		
Biomass Burning		1.1⁽¹¹⁾	1.7	0.7	0.5			0.7		0.7	0.5-1.7
Residue Burning	0.01		1.6							0.04	
Savanna Burning ¹¹										0.3	
Others ¹²			0.1							0.4	
Industry and Fossil Fuel (Stationary and Mobile) Combustion¹³		1.7	0.9		0.8		0.7 - 1.3	0.7	1.3	0.9	0.7-1.7
Wastewater, Aquaculture and Others		0.2	0.4	0.3				0.2	0.3	0.3	
Wastewater		0.2	0.2	0.3				0.2	0.3	0.2	
Aquaculture										0.05	
Solvent and Other Product Use			0.2							0.05	
Land Use Change¹⁴				-0.6	-0.9		0 to -0.9			-0.9	
Ocean				1.0						0.2⁽¹⁵⁾	
Total		6.8	7.6	6.5	5.4	-	5.6-6.5	6.7	8.4	5.3	5.3-8.4

- 2010 estimates; The United Nations Food and Agriculture Organization (FAO) estimates agricultural N₂O emissions by applying IPCC Tier 1 EFs to their country data gathered from national publications and questionnaires.
- 2008 estimates; the Emissions Database for Global Atmospheric Research (EDGAR) category “Indirect N₂O from non-agricultural NH₃ and NO_x” is partitioned between “Biomass Burning” and “Industry and Fossil Fuel Combustion” and weighted by their total direct emissions. The EDGAR database uses a blend of private and public data, applying IPCC Tier 1 EFs to estimate both non-agricultural and agricultural N₂O emissions (with the exception of biomass burning, where they apply EFs described in Andreae and Merlot, 2001).
- 2006 estimates
- 2005 estimates; agriculture estimates include human waste emissions
- Mix of data from 2000 and 1994
- 2000 estimates; agriculture estimates include human waste, aquaculture, and biomass burning emissions
- Effects of atmospheric deposition are included in the agriculture sector, although a portion of the deposition comes from other sectors
- 2006 estimates for agriculture and waste (adapted by Syakila and Kroeze, 2011), 1989 estimates for industrial/energy.
- The UNEP estimates for agriculture, biomass burning, wastewater, aquaculture, and land use change are from chapters within this report.
- The FAO estimates are adopted in Chapter 4 of this report. This estimate does include indirect emissions from downwind and downstream ecosystems, but does not include sewage wastewater emissions.
- Includes category “large-scale biomass burning” which denotes savannah burning, forest fires, peat fires, grassland fires, decay of wetland/peatland and post burn decay after forest fires, agricultural residue burning, and other vegetation fires.
- “Other” biomass burning includes tropical, temperate and boreal forest fires, tropical peat fires, and fuelwood fires.
- Several literature sources combine emissions from industry and/or energy and transport into one overall estimate.
- The Syakila and Kroeze (2011) estimate of reduced natural emissions is for pre-industrial land use change only. Crutzen et al. provide only a range, so we use Davidson’s (2009) estimate for post-industrial tropical deforestation
- Emissions from the ocean due to anthropogenic N deposition should be included in indirect emission factors for agriculture and other sectors, but are probably underestimated, so we include this estimate from Suntharalingam et al. (2012).

to historic and on-going deforestation, which is neglected in many other inventories. Our best estimate of gross anthropogenic emissions is 6.2 Tg N₂O-N/yr, and our best estimate of reduced soil emissions due to anthropogenic land-use change is 0.9 Tg N₂O-N/yr, resulting in a best estimate of 5.3 Tg N₂O-N/yr for net anthropogenic emissions. Without this adjustment to the bottom-up inventory estimates, the bottom-up and top-down approaches would not agree.

To put the anthropogenic emissions of N₂O into perspective, UNEP (2012) estimates that these emissions make up about 6% of total global greenhouse gas emissions (in carbon dioxide equivalents). This makes N₂O the third most important greenhouse gas in terms of global emission after carbon dioxide and methane.²⁴

The next section describes the breakdown of N₂O emissions from the various economic sectors and the factors responsible for the emissions. In this section, we will compare sectoral emissions with total current gross anthropogenic emissions of 6.2 Tg N₂O-N/yr.

3.3.3. Anthropogenic emissions by sector

Agriculture (Chapter 4)

Agriculture is the largest source of anthropogenic N₂O emissions, responsible for 4.1 Tg N₂O-N/yr (3.8-6.8 Tg N₂O-N/yr) or 66% of total gross anthropogenic emissions (Table 3.1). Emission estimates include direct soil emissions from synthetic nitrogen fertilizer and manure application and indirect emissions that occur from downstream or downwind water bodies and soils after nitrate leaches away from croplands and after nitrogen emitted from croplands as ammonia or nitrogen oxide gases falls back to the earth as atmospheric nitrogen deposition. Also included are N₂O emissions resulting from crop residues, manure management, cultivation of organic soils, and crop biological nitrogen fixation (C-BNF). The central factor responsible for agricultural N₂O emissions is a lack of synchronization between crop nitrogen demand and soil nitrogen supply. On average, around 50% of nitrogen applied to soils is not taken up by the crop (see Chapter 4). Inputs of nitrogen to agricultural soils are mainly from synthetic nitrogen fertilizer and manure application, with additional supply from legume nitrogen fixation, crop residues, and nitrogen deposition.

Industry and fossil fuel combustion (Chapter 5)

The industry sector plus fossil fuel combustion (stationary combustion and transportation) together are responsible for about 0.9 Tg N₂O-N/yr (0.7-1.6 Tg N₂O-N/yr) or 15% of total gross anthropogenic N₂O emissions. Nitric and adipic acid production are the major industrial sources. Nitric acid is mainly used as a feedstock in the production of explosives and nitrogen fertilizer, particularly ammonium nitrate, with N₂O emitted during the ammonia oxidation process (USEPA, 2012). Adipic acid is a key feedstock in synthetic fibre production, with N₂O resulting from the use of nitric acid to oxidize several organic chemicals (Schneider et al., 2010). Stationary combustion (mainly coal power plants) is the principal source of N₂O from the energy sector.

Emissions of N₂O from this sector arise via the oxidation of both atmospheric N₂ and organic nitrogen in fossil fuels, with the extent of emissions dependent on the amount of organic nitrogen in the fuel, the operating temperature, and the oxygen levels during combustion (USEPA, 2012). N₂O from transport is released primarily by catalytic converters used to control NO_x, carbon monoxide, and hydrocarbons in tailpipe emissions.

Biomass burning (Chapter 6)

Biomass burning is currently responsible for about 0.7 Tg N₂O-N/yr (0.5-1.7 Tg N₂O-N/yr) or 11% of total gross anthropogenic emissions. This includes crop residue burning, forest fires (resulting from both natural and human activities), and prescribed savannah, pasture, and cropland burning. It also includes N₂O emissions from household biomass stoves. N₂O is released via the oxidation of organic nitrogen in biomass during combustion. Although some wildfires are ignited naturally by lightning, all emissions from biomass burning have been attributed as anthropogenic emissions because it is impossible to separate out which wildfires are ignited by humans. Furthermore, anthropogenic climate change may also be increasing natural fire frequency and severity (Pechony and Shindell, 2010).

Wastewater, aquaculture and other sources (Chapter 7)

This category includes a variety of sources, including N₂O emissions from wastewater, aquaculture, the ocean, and emission reductions from land conversion. N₂O emissions from wastewater were 0.2 Tg N₂O-N/yr in 2010, or 3% of total gross anthropogenic emissions. This includes N₂O emitted either directly from wastewater effluent or from bioreactors removing nitrogen in biological nutrient removal plants (Law et al., 2012). A small amount of N₂O is also emitted in aquaculture (<0.1 Tg N₂O-N/yr in 2010) through the release of nitrogen wastes to surface waters where nitrogen is transformed and released as N₂O emissions. Various human-related changes to the oceanic environment have affected the amount of N₂O emissions produced by the oceans. These include: (i) increases in atmospheric nutrient deposition (Duce et al., 2008; Suntharalingam et al., 2012), (ii) the formation of low- or no-oxygen zones in the coastal environment (Gruber, 2008; Keeling et al., 2010), (iii) changes in marine productivity associated with ocean stratification and circulation change (Dutreuil et al., 2009), (iv) ocean acidification impacts on nitrification (Beman et al., 2011), and (v) eutrophication of coastal zones (Galloway et al., 2004).

Increased nitrogen deposition onto the ocean has been estimated to have increased the oceanic N₂O source by 0.2 Tg N₂O-N/yr (0.08–0.34 Tg N₂O-N/yr) or 3% of total gross anthropogenic emissions (Suntharalingam et al., 2012). The other mentioned impacts have not been quantified on the global scale. In principle, increased oceanic emissions due to nitrogen deposition should be included in the indirect emission estimates from agricultural, energy, and transportation sources, but they are included here as a separate category because it is speculated that the oceans may have been under-represented in calculations of emissions from downwind and downstream ecosystems.

²⁴ UNEP used a different estimate of anthropogenic N₂O emissions than used in this report.

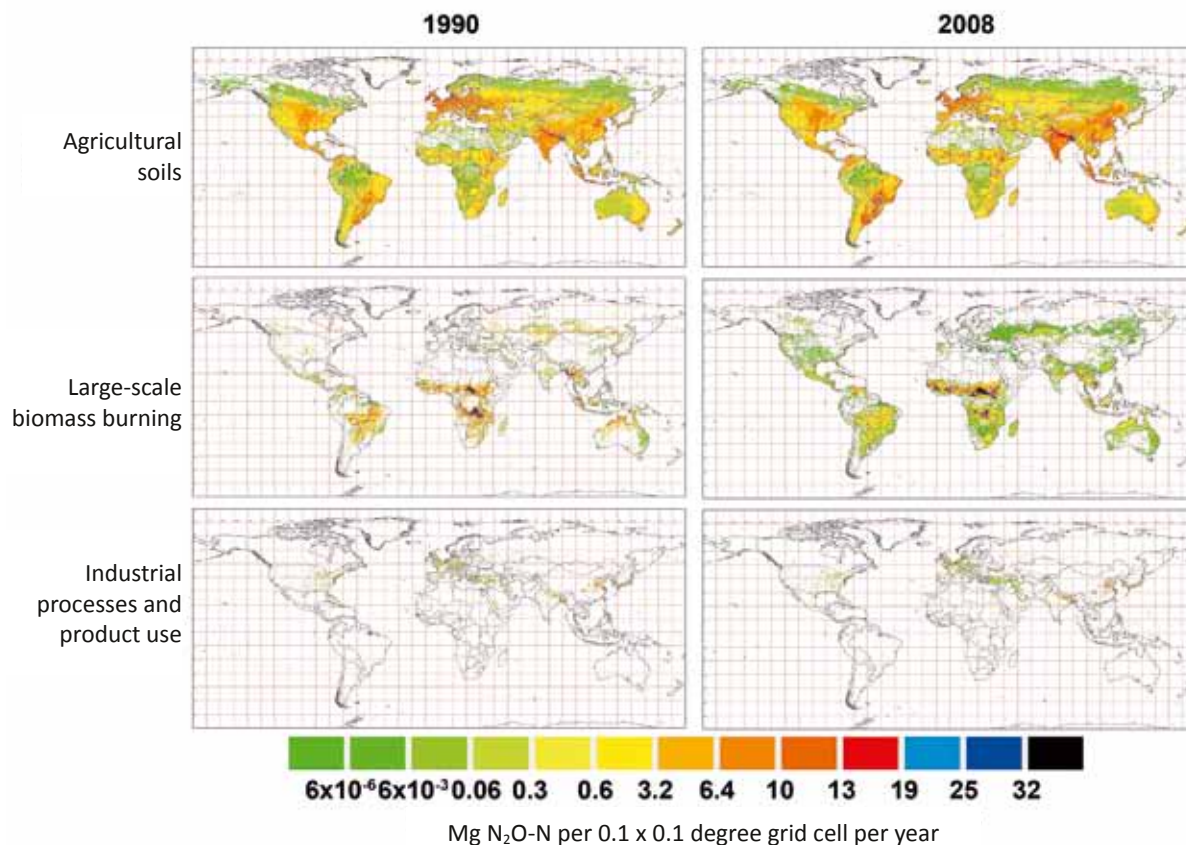


Figure 3.2: Global maps of direct emissions from agricultural soils, large scale biomass burning, and industrial processes (mostly adipic and nitric acid production) for 1990 and 2008 from the Emissions Database for Global Atmospheric Research (EDGAR), version 4.0 (2009) (<http://edgar.jrc.ec.europa.eu>). Units are tons of N₂O-N per 0.1 x 0.1 degree grid cell per year. Note that this size grid cell is about 123 km² at the equator and declines with increasing latitude, approaching zero near the poles.

Because tropical forest soils are a large natural source of N₂O emissions, tropical deforestation should be considered as a significant anthropogenically induced change in emissions. Soil N₂O emissions from recently converted tropical forests may initially increase, but the long-term trend is for emissions from the pasture soils and degraded land soils to be lower than those from intact, mature tropical forests, resulting in current estimates of a decreased source of 0.9 Tg N₂O-N/yr. This decreased soil source of N₂O due to anthropogenic activity is equal to about 15% of total gross anthropogenic emissions, so that estimated net anthropogenic emissions are 15% lower than gross anthropogenic emissions (Davidson, 2009).

3.4 Trends in emissions over the last 20 years

Figure 3.2 illustrates how N₂O emissions from three of the most important sectors of the Emissions Database for Global Atmospheric Research (EDGAR, 2009) have changed from 1990 to 2008. The dominance of emissions by agricultural soils is clear, with the importance of South Asia, parts of Latin America and especially East Asia as sources of these emissions growing in the last two decades. Large-scale biomass burning emissions are most important in tropical savannah regions. Industrial emissions are most important in developed countries and are growing in South and East Asia.

3.5 Emission projections

Projections of future emissions depend upon assumptions about changes in:

- Population growth rates.

- Per capita consumption of calories and protein needed for human nutrition and the avoidance of overconsumption.
- Relative sources of vegetable versus animal products for meeting food demands.
- Rates of wastage/loss of food from production to consumption.
- Nutrient use efficiency in crop and animal production systems.
- Production of new fixed nitrogen for agriculture (including biofuels) and aquaculture.
- Emissions of NH₃ and NO_x from all sectors, which contribute to nitrogen deposition on native soils and oceans.
- Fire frequency, including slash-and-burn agriculture, pasture clearing and wildfire.
- Industrial sectors.
- Land-use change.
- Energy sector technology and demand for biofuels.
- Climate and its effects on nitrogen cycle processes.

Climate change also has an effect on the rate of N₂O emissions from water bodies and soils under native vegetation, but this effect is not well represented in current models (Pinder et al., 2012) and it is not dealt with here. Most published projections of future emissions focus on assumptions about changes in emissions from agriculture, biomass burning, energy, transportation, and industry. Here, three sets of published emission scenarios were aggregated to characterize the potential range of future anthropogenic N₂O emissions:

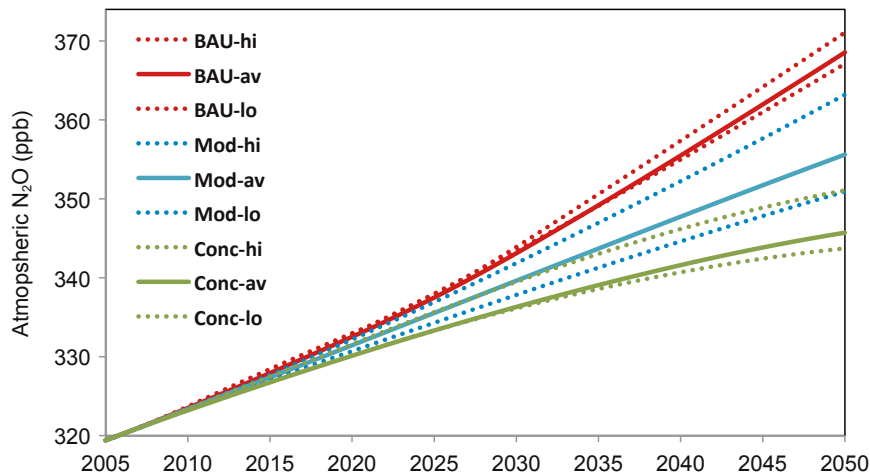


Figure 3.3: Projected atmospheric concentrations of N₂O for groupings of published scenarios for business-as-usual (“BAU” in red, including RCP 8.5, SRES A2 and Davidson’s S1), moderate mitigation (“Mod” in blue, including RCP 4.5, RCP 6.0, SRES A1, SRES B1, and Davidson’s S2 and S3), and concerted mitigation (“Conc” in green, including RCP 2.6, SRES B2, and Davidson’s S4 and S5), based on Nakicenovic et al (2000), Van Vuuren et al (2011a) and Davidson (2012). Solid lines show the average (av) for each grouping and dotted lines show the high (hi) and low (lo) estimates. All projections have been adjusted to a common emission estimate baseline in 2005 consistent with this report’s best estimate of net anthropogenic emissions of 5.3 Tg N₂O-N/yr.

- Davidson (2012) used FAO projections of population and dietary demands to estimate fertilizer and manure demands and subsequent N₂O emissions, including five variants (S1-S5) of mitigation and dietary habits.
- The Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) created four major global greenhouse gas emissions scenarios (A1, A2, B1 and B2) based on the degree of globalization vs. regionalization and the priority given to economic vs. social and environmental objectives. These were used in the IPCC’s Third and Fourth Assessment Reports.
- The Representative Concentration Pathways (RCP; Van Vuuren et al., 2011a) are widely viewed as the next iteration of SRES, with four scenarios based on differing radiative forcing levels rather than emissions (RCP 2.6, 4.5, 6.0 and 8.5, with the numbers referring to different radiative forcing levels). They were developed for use with climate simulations for climate change analyses.

These studies have different base years and employ different inventory sources. In order to make their results comparable, all emission estimates from these scenarios were normalized to the best estimate of 2005-2010 average net anthropogenic emissions from this report (5.3 Tg N₂O-N/yr).

The scenarios are organized into three groups:

- Business-as-usual scenarios** with little or no mitigation. The RCP 8.5, SRES A2, and Davidson’s S1 scenarios are business-as-usual (BAU) scenarios, which, on average, project a near doubling of annual net anthropogenic emissions by 2050 relative to 2005.
- Moderate mitigation scenarios.** The scenarios RCP 4.5, RCP 6.0, SRES A1, SRES B1, and Davidson’s S2 and S3 are “moderate mitigation” scenarios, defined here as scenarios showing emission trends that are higher than 2005 emissions in 2050 but below BAU. The range of increased annual net anthropogenic emissions in 2050 compared to 2005 is 7 to 64%.

- Concerted mitigation scenarios.** The RCP 2.6, SRES B2, and Davidson’s S4 and S5 mitigation scenarios are called “concerted” because they lead to emissions in 2050 that are below the 2005 level. In 2050 these scenarios are 2 to 34% below 2005 net annual anthropogenic emissions.

The scenarios of annual emissions are presented graphically in Figure 8.1 of Chapter 8. In Chapter 8 we also present further analysis of the three published sets of scenarios combined with a new set of scenarios developed in this report.

Here in Figure 3.3 we present the implications of the three published sets of scenarios on the atmospheric concentration of N₂O. The concerted mitigation scenarios result in near stabilization of atmospheric N₂O between 340 and 350 ppb by mid-century and probable stabilization before the end of the century, whereas N₂O concentrations continue rising for the BAU and moderate mitigation scenarios (Figure 3.3). The differences in emissions and concentrations between the BAU scenario and the mitigation scenarios reveal the potential for considerable emission reductions, which are discussed in Chapter 8.

One caveat of these projections is that they all begin in 2005, and significant differences are already apparent in their trajectories by 2013. So far (up to 2013), actual global N₂O emissions have been closer to BAU trajectories than the mitigation trajectories. Missing from these projections are the possible impacts of expansion of biofuels production due to the wide uncertainty bounds surrounding the potential land area devoted to biofuel, energy demand for biofuels and their fertilizer requirements. These projections are therefore explored separately in Box 3.1.

3.6 Conclusions

- Natural N₂O emissions are 10.2 to 12.1 Tg N₂O-N/y but they do not contribute to the increase of N₂O in the atmosphere. This is because about the same amount of N₂O is removed from the atmosphere, primarily by natural chemical reactions in the stratosphere, as is emitted to the atmosphere through natural processes.

Box 3.1. A major source of uncertainty in N₂O emission projections: Biofuel scenarios

The potential impacts of expanding first- and second-generation biofuels beyond 2020 are highly uncertain. In addition to uncertainties about total biofuel production, the nitrogen fertilization rates needed for producing second- or third-generation fuel stocks and the N₂O emission factors for those cultivation practices are not known. Fertilization rates and emission factors for rapidly growing trees and native grasses, forbs, and shrubs may be much lower than for most current food and fibre crops. Two methods were used here to bound the range of future N₂O emissions from biofuels – one based on the potential to deploy bioenergy from the demand and supply side, and the other based on total land available for biofuel crop cultivation.

For the first method, Edenhofer et al. (2011) estimate a bioenergy deployment range of 100-300 EJ/yr by 2050, which takes into account soil conservation and biodiversity goals, as well as potential water scarcity and the use of land for subsistence farming (Edenhofer et al., 2011; Creutzig et al., 2012).²⁵ This approach generates estimates of 0.02-8.1 Tg N₂O-N/yr from biofuels by 2050, depending on the fuel source and the total amount of bioenergy deployed, with a central estimate of 2.1 Tg N₂O-N/yr.

The second method focuses on the amount of land potentially available to cultivate biofuel crops. Estimates range from 60-3700 Mha (covering 0.4%-28% of the earth's land surface, excluding Greenland and Antarctica), with a number of estimates clustering between 240-500 Mha (Creutzig et al., 2012).²⁶ Using this approach, N₂O emissions were estimated to be 0.08-4.9 Tg N₂O-N/yr (with a central estimate of 0.5 Tg N₂O-N/yr)²⁷, depending on the amount of land devoted to biofuel crop cultivation.

The estimates calculated here are considerably lower than the Melillo et al (2009) estimates of 16.1-18.6 Tg N₂O-N/yr by 2100, though they are consistent with the Erisman et al (2008) estimate of 0.9 Tg N₂O-N by 2100. These data illustrate the huge uncertainty that still remains in future estimates of N₂O emissions from biofuels. Comparing these estimates from <1 to >18 Tg N₂O-N/yr to the range of the aggregated RCP, SRES and Davidson (2012) scenarios (4.4 to 9.9 Tg N₂O-N/yr) demonstrates that biofuels could either remain a relatively trivial source or become the most significant source of anthropogenic N₂O emissions at some point this century. Energy and climate policy decisions in the coming decades as well as the pace of technical innovation will be among the major determinants of future N₂O emissions from biofuels.

25 For this calculation, it was assumed that by 2050 all bioenergy demand will be supplied by second-generation biofuels. Given data constraints, the estimation focused on jatropha (*Jatropha curcas*), miscanthus (*Miscanthus x giganteus*), eucalyptus (*Eucalyptus cinera*) and switchgrass (*Panicum virgatum* L). To estimate emissions, the range of published N₂O emission factors for these biofuels (which varies between 0.2 and 27.1 g N₂O-N/kJ) (Hoefnagels, 2010), were used.

26 In comparison, Melillo et al (2009) estimate that about 2000 Mha of biofuel crop cultivation will be needed by 2100 to stabilize atmospheric CO₂ concentrations at 550ppm (40%-90% of which would come from clearing forest for new crop land), while Van Vuuren et al (2011) estimated that 3000-4000 Mha will be needed by 2100 in order to reach the RCP 2.6 scenario for total radiative forcing of all greenhouse gases.

27 These calculations assume an average fertilizer application rate of 100 kg N/ha/yr for land devoted to biofuel crops, as was assumed by Erisman et al. (2008), although some crops may require less nitrogen fertilizer. These calculations also use the IPCC (2006) direct and indirect default emission factors.

- Net anthropogenic N₂O emissions are now (2005-2010) about 5.3 Tg N₂O-N/yr. These emissions are not being removed from the atmosphere at a fast enough rate to prevent build-up of N₂O in the atmosphere.
- Agriculture currently accounts for 56-81% of gross anthropogenic N₂O emissions. A major reason for this is the lack of synchronization between crop nitrogen demand and soil nitrogen supply. On average, around 50% of nitrogen applied to soils is not taken up by the crop. Future N₂O emissions from agriculture will be determined by several factors, including population, dietary habits, and agricultural management to improve nitrogen use efficiency.
- Industry, energy and transport sectors are responsible for 10-25% of gross anthropogenic N₂O emissions and are also the source for much of the NO_x emissions that contribute to indirect N₂O emissions from land and the oceans.
- Emission reductions under the concerted mitigation scenarios lead to a near stabilization of atmospheric concentration of N₂O below 350 ppb by the middle of the current century. However, under the business-as-usual and moderate mitigation scenarios atmospheric N₂O concentrations continue to climb throughout the century.
- The impact of growing demand for biofuels on future projections of N₂O emissions is highly uncertain, depending mostly on the types of plants grown, their nutrient management, the amount of land dedicated to their cultivation, and the fates of their waste products. Considering the area of land that could be devoted to biofuel crops, the nitrogen fertilizer application rates, and the management practices, N₂O emissions from second and third generation biofuels could remain trivial or could become the most significant source to date. Therefore, research is urgently needed to reduce the uncertainty of the future impact of biofuels on N₂O and other aspects of the environment.



Copyright: All images from Shutterstock. Top, left to right: Symbiot, Kekyalaynen, Symbiot; Bottom, left to right: GOLFX, Peter J. Wilson, CreativeNature.nl

Part 2

Solutions to the N₂O Challenge

Chapter 4

Reducing N₂O Emissions from Agricultural Sources

Lead Authors: Oene Oenema (Wageningen University, The Netherlands), Xiaotang Ju (China Agricultural University, P.R. of China), Cecile de Klein (AgResearch Invermay, New Zealand)

Contributing Authors: Marta Alfaro (Institute for Agricultural Research, Chile), Agustin del Prado (BC3 Basque Centre for Climate Change, Spain), Jan Peter Lesschen (Wageningen University, The Netherlands), Xunhua Zheng (LAPC, Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), P.R. of China), Gerard Velthof (Wageningen University, The Netherlands), Lin Ma (Wageningen University, The Netherlands), Bing Gao (China Agricultural University, P.R. of China), Carolien Kroeze (Wageningen University, The Netherlands), Mark A. Sutton (NERC Centre for Ecology and Hydrology, UK).

4.1. Introduction

Chapter 3 reviewed the many sources of anthropogenic N₂O in the atmosphere and highlighted the fact that agriculture is its largest source. In this chapter, we briefly review the sources of N₂O emissions in agriculture and possible strategies for reducing these emissions. For the purpose of this chapter, “agriculture” includes (1) producing crops for food, feed and biofuel, and (2) raising animals for meat, egg and dairy products. Aquaculture is not covered here, but in Chapter 7.

4.2. Sources of N₂O emissions from agriculture

Nitrogen is essential for producing food and feed; it is a constituent of protein, amino acids, vitamins, and nucleic acids, which have critical functions in plants, animals and humans. Application of nitrogen generally boosts the growth and development of crops, and hence the production of food. Similarly, animals grow and develop well when there are sufficient proteins and essential amino acids in their feeds. However, nitrogen also causes N₂O emissions. On average 1% of the nitrogen applied to crop land is directly emitted as N₂O into the atmosphere, depending on nitrogen source and environmental conditions (IPCC, 2001, 2006). In addition, there are N₂O emissions related to the storage and management of animal manures, the recycling of residues and wastes, the production of synthetic fertilizers, and some additional nitrogen losses.

Current total N₂O emissions from global agriculture are estimated at approximately 4.1 Tg N₂O-N/yr (range: 3.8 - 6.8)²⁸. Nine main sources of N₂O emissions are distinguished (Table 4.1) and these can be classified as either direct or

indirect²⁹. Each of these sources has a specific emission factor³⁰. Fertilizer and animal manure (including droppings from grazing animals) are the largest sources of emissions. Table 4.1 indicates that indirect emissions accounted for approximately 22% of total emissions in 2010. Nitrogen-fixing crops including soybean, clover, alfalfa and other leguminous crops have not been distinguished as separate N₂O sources because emissions during their growth are considered to be negligible (Rochette and Janzen, 2005). However, the total nitrogen stored in these plants is relatively large and they contribute significantly to N₂O emissions as crop residues (Marinho et al. 2004, Mosier et al., 2006, Herridge et al., 2008).

29 Emissions associated with the microbial nitrification and denitrification of fertilizer and manure nitrogen that remains in agricultural soils or animal waste management systems are referred to as direct emissions, while those associated with the volatilization, leaching or runoff of nitrogen from agricultural soils and animal waste management systems are referred to as indirect emissions.

30 Though source-specific, there is a considerable uncertainty in N₂O emission factors (Rypdal and Winiwarter, 2001), especially at field and farm scales, but less at the global scale (e.g., Kros et al., 2012, Leip et al., 2011, Butterbach-Bahl et al., 2013). The large uncertainty at lower scales is related to the diversity of agriculture and environmental conditions, the complexity of the N₂O producing processes and their controls (Robertson and Tiedje, 1987; Davidson et al., 2000), but also to the uneven spread of studies, with few field measurements in Africa (Baggs et al., 2006; Chapuis-Lardy et al., 2009). According to a default inventory methodology (IPCC, 2006), it is assumed that N₂O emissions are linearly related to the amounts of N input, representing 1% of nitrogen applied, with an uncertainty range of 0.03 to 3%. However, some authors have challenged this linearity (McSwiney and Robertson, 2005; Stehfest and Bowman, 2006; Cardenas et al., 2010; Hoben et al., 2011), and argue that emissions increase more than proportionally with nitrogen applied. Furthermore, emission factors have been differentiated according to nitrogen-input sources and environmental conditions. For example, Lesschen et al. (2011a) and Leip et al. (2011) derived fertilizer type, crop residue type, land-use, soil type and rainfall specific emission factors for Europe. For Mediterranean agriculture, Aguilera et al. (2013) differentiated emission factors according to fertilizer type and irrigation scheme. However, lack of activity data (e.g. N fertilizer type and application, N excretion) hamper the reduction of uncertainties (Philibert et al., 2012; Rosenstock et al., 2013).

28 Estimated range taken from Table 3.1 in Chapter 3 of this report.

Table 4.1. Emissions of N₂O from agriculture per continent in 2010, estimated here using the Tier 1 IPCC (2006) approach with source-specific emission factors and national-level activity data from FAOSTAT.

General characteristics & Sources of N ₂ O	Asia	Africa	Europe	North America	Latin America	Oceania	Global Total
Human population, billion	4.26	1.02	0.74	0.34	0.59	0.04	7
Agricultural utilized area, Mha	1633	1170	469	474	737	412	4895
Synthetic fertilizer N use, Tg	67	3	14	14	7	2	107
Manure N excretion, Tg	39	22	12	7	22	5	107
Grain production, Tg	9455	1669	1818	2170	2101	213	17426
Direct Emissions, Gg N₂O-N							
Applied fertilizer	670	30	135	135	74	15	1059
Nitrogen fertilizer production*	-	-	-	-	-	-	-
Manure management	109	12	45	29	20	4	219
Applied manure	50	5	63	25	22	1	166
Grazing animals	387	331	55	73	342	63	1251
Applied crop residues	119	17	40	45	32	4	257
Burning crop residues**	6	2	1	2	2	0	13
Drainage of peatlands***	90	11	62	24	3	10	200
Indirect Emissions, Gg N₂O-N							
Emission from loss of nitrates (NO ₃) to surface and ground water and volatilization of ammonia (NH ₃)	420	106	127	97	128	26	904
Total emissions, Gg N₂O-N	1852	514	528	429	623	123	4069
Emissions, kg N₂O-N per capita	0.4	0.5	0.7	1.3	1.1	3.1	0.6
Emissions, kg N₂O-N per ha	1.1	0.4	1.1	0.9	0.8	0.3	0.8
<p>* N₂O emissions from industrial processes for fertilizer production are discussed in Chapter 5.</p> <p>** Emission reduction options for agricultural burning are discussed in Chapter 6</p> <p>*** Peatlands are organic matter rich soils. Because of their high organic matter content, they may serve as sources of greenhouse gases including carbon dioxide, methane and N₂O. Human activities (land-use change and drainage of the soil for agriculture, forestry and peat extraction) result in the emission of especially carbon dioxide and N₂O into the atmosphere.</p>							

Asia is the continent with the largest N₂O emissions (Table 4.1), reflecting the fact that it also has the largest agricultural area and population. On a per capita basis, Asia has the lowest estimated N₂O emissions, followed by Africa and Europe. Expressed per surface area of agricultural land, emissions are highest in Asia and Europe and lowest in Oceania and Africa. The largest source of N₂O emissions in Asia, Europe and North America is the use of fertilizers for food, feed and biofuel production, while in Africa, Latin America and Oceania, the largest source is nitrogen excreted from grazing animals.

4.3. Options for emission reductions

Though intrinsically related to the cycling of nitrogen and the production of food, not all N₂O emitted from agriculture should be considered 'inevitable'. There are possibilities for reducing N₂O emissions, which can be grouped into the following broad strategies:

- Changing diet and reducing food loss/waste.
- Improving nitrogen use efficiency in crop and animal production.
- Adopting technologies and management practices that decrease the fraction of input nitrogen that is released as N₂O (i.e., the emission factor).

These strategies, which may be combined, depending on local situations, to reduce N₂O emission in the food

production, processing and consumption chain (Figure 4.1) are further discussed below.

4.3.1. Changing diet and reducing food loss/wastes

Changing diet

Food choices have major impacts on nitrogen use and N₂O emissions per capita. For example, emissions associated with the production of animal-derived protein are about a factor of ten larger than those associated with the production of plant-derived protein (Galloway and Cowling, 2002; Figure 4.2). Within animal-derived food types, the production of ruminants (cattle, sheep and goat) releases more N₂O per kg of product than pork and poultry. Hence, reducing the intake of animal-derived protein, especially by consumers in affluent countries, would reduce demand and consequently production of these food types, thereby decreasing associated N₂O emissions. Reay et al. (2011) showed that the average European consumes 70% more protein than needed to meet dietary requirements (WHO, 2007) indicating a potential to reduce N₂O emissions without compromising good nutrition.

Apart from reduced N₂O emissions, dietary change has the additional benefits of improving human health and reducing ecological impacts associated with animal food production (Steinfeld et al., 2006; Erisman et al., 2008; Sutton et al., 2011a,b). However, it is also obvious that reducing the consumption of

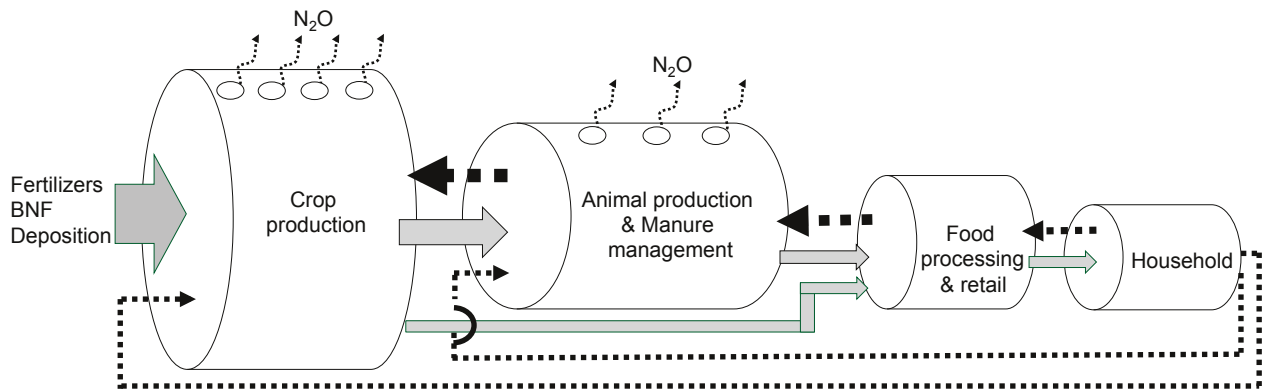


Figure 4.1: A food system approach for reducing N_2O emissions in the production, processing and consumption of food. The cylinders represent ‘ N_2O -leaky’ compartments of the food system. The large grey arrow at the left indicates ‘new’ nitrogen inputs via fertilizers, biological nitrogen fixation (BNF) and atmospheric deposition. Smaller grey arrows indicate the flow of nitrogen in food and feed from production to consumption in households. Dashed black arrows indicate recycled nitrogen in manure, residues and wastes (based on Ma et al., 2010a, 2012).

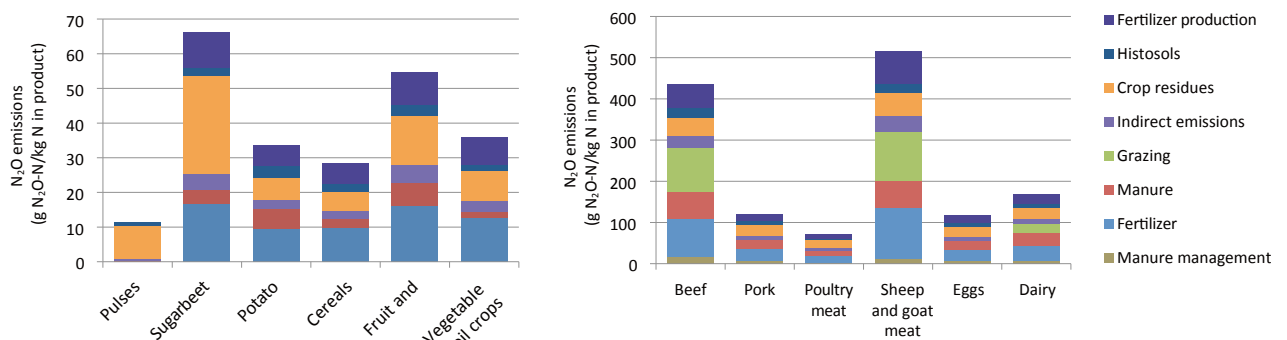


Figure 4.2: Mean N_2O emissions associated with the production of plant-derived food products (left panel) and animal-derived food products (right panel) in the European Union in 2004, expressed in $g N_2O-N$ per unit of protein-N in the products (based on Lesschen et al., 2011b). **Note scale difference.** Note also that emissions derived from fertilizer production are based on the relatively large share of ammonium nitrate-based nitrogen fertilizers in the EU, while mitigation measures in fertilizer plants were not in place everywhere by 2004 (see Chapter 5).

animal-derived protein is not relevant or an option for millions of people in South Asia, Africa, and elsewhere who are currently consuming very low levels of this protein.

Reducing food loss/waste

Globally, an estimated 20 to 40% of food produced is either lost or wasted at various stages in the food production-consumption chain (Parfitt et al., 2010; Gustavsson et al., 2011). For example, the annual amount of wasted food in China is now equivalent to the food needed by 200 million people (Ren, 2013). According to UNEP (2012), American consumers throw away around 25% and British consumers about 33% of food purchased. Furthermore, food is lost in developing countries due to lack of infrastructure for the processing, transportation and storage of produced food. Reducing food loss/waste may proportionally decrease global food requirements, thus, reducing N_2O emissions associated with production. Assuming a wastage reduction of 50%, i.e. from the current 20 to 40% loss to 10 to 20%, (Gustavsson et al., 2011; Kummu et al., 2012), total agricultural N_2O emissions could also decrease by 10 to 20%.³¹

Options for minimizing food wastage include increased public awareness about the importance of not wasting food, improved food labelling, relaxation of quality standards that do not affect taste or quality of food, developing markets

for sub-standard products or consumable products deemed as waste, and change in business behaviour aimed at waste reduction. Food loss in developing countries can be substantially lowered by providing necessary infrastructure to small-holders (UNEP, 2012).

It must be noted however, that some level of wastage is inevitable in the food production-consumption chain. Recycling of these wastes as manure for agriculture could potentially reduce the quantity of synthetic fertilizers used in agriculture, thereby decreasing the total N_2O emissions in the food system.

The two strategies discussed above fall under the overall concept of sustainable food systems³² as described in UNEP (2012).

4.3.2. Increasing nitrogen use efficiency in crop and animal production

Crop production

Although defined in various ways, nitrogen use efficiency (NUE) generally provides an indication on how well nitrogen applied to crops is taken up and converted to crop yield (e.g., Dobermann, 2007). NUE is high when the amount of produce per unit of nitrogen applied is high. If NUE is high, the risks of

31 This is based on the assumption that total N_2O emissions from agriculture are linearly related to the amount of food produced. Hence, a 10-20% reduction in food production will result in similar reduction in N_2O emissions.

32 Sustainable food systems apply sustainability practices in the production, processing, distribution, storage, marketing and consumption of food so as to increase human well-being and minimize impact on the environment. It enables the production of sufficient, nutritious food, while conserving the resources that the food system depends on (UNEP, 2012).

nitrogen losses and N₂O emissions are relatively low. Hence, efforts aimed at improving NUE can yield dual benefits: an increase in crop yield and reduced nitrogen losses, including N₂O emissions (Burney et al., 2010; Thomson et al., 2012).

Emissions of N₂O from crop production rise with increased nitrogen input from fertilizers, manures, composts, wastes, and crop residues (Bouwman et al., 2002; Snyder et al., 2009). However, emissions per unit of crop produce tend to decrease with increased nitrogen input until an optimum input level is reached. Beyond this level, N₂O emissions per unit of crop produce increase sharply because an increasing fraction of applied nitrogen is not utilized by the crops (van Groenigen et al., 2010; Venterea et al., 2011). Hence, a straightforward strategy for increasing NUE and consequently reducing N₂O emissions is to apply only the amount of nitrogen needed for crop growth. This falls under the overall idea of nutrient management³³.

A notable nutrient management strategy is the “4R nutrient stewardship” also referred to as the “4Rs”. This strategy encourages the application of the right nutrient sources, in the right amount, at the right time and in the right place³⁴ (IPNI, 2012). For it to be successful, the 4Rs requires site, soil and crop type-specific knowledge and information, accompanied by appropriate technologies³⁵ and best management practices. Snyder and Fixen (2012) reported that nitrogen uptake of more than 70% could be achieved for many cereal crops when site-specific nutrient management practices based on the 4Rs are implemented. This is a significant increase over current levels since, for example, nitrogen recovery by corn (*Zea mays*) typically ranges between 40 to 50% (Dobermann 2007).

For global food security, large efforts have to be made to further increase crop yields through plant breeding (increasing the genetic potential of the crop), improved crop husbandry (appropriate seeding time and planting density, appropriate weeding), improved irrigation and drainage management³⁶, and improved pest and disease management. When properly combined, these efforts have the potential to increase crop yield and nitrogen use efficiency simultaneously (Chen et al., 2011; Hirel et al., 2011). Other options for enhancing NUE

include cover cropping³⁷, multiple cropping³⁸, buffer strips³⁹, and conservation tillage⁴⁰.

Studies so far indicate that, depending on the local situation, N₂O emissions per surface area and per unit crop produced may decrease by 10 to 60% through the implementation of the above options (Table 4.3). It must be noted however, that significant investments in education, training, demonstration and development of site-specific technologies are needed in order to be able to implement NUE improvement measures. This is because these measures would have to be implemented by the millions of small-holder farmers in the world in site-specific ways. Also, different areas may require different priorities and strategies. For example, crop yields have been stagnant in Africa during the last four decades (Lobell et al., 2009), in part because breeding efforts have not focused on crops predominantly grown in Africa. Meanwhile poor functioning markets have largely prohibited the use of technologies and management practices to increase yields and NUE.

Animal production

Although animals do not directly release N₂O into the atmosphere (or only in trivial amounts), animal wastes are a large source of nitrogen and hence, N₂O production (Steinfeld et al., 2006). Animals convert between 10 to 45% of the nitrogen in their feed into protein nitrogen in meat, milk, eggs, wool and hides, depending on animal species, feed quality and management. The remaining 55 to 90% of the nitrogen in feed is excreted in dung and urine.

Increasing nitrogen use efficiency (NUE) in animal production is increasing the percentage of feed nitrogen that is converted into animal products (Powell et al., 2010). By doing so, less animal feed and less nitrogen are needed to produce a unit of meat, milk, egg, wool and hides, and hence, N₂O emissions associated with animal production will decline. Increasing NUE in animal production requires targeted combinations of animal breeding⁴¹, improvements in feed quality and feed management⁴², and improvements in herd management⁴³ (Steinfeld et al., 2010, Herrero et al., 2010, Bai et al., 2013). We estimate that a site-specific implementation of these management measures could greatly increase animal productivity and decrease the

33 Nutrient management involves putting in place practices aimed at using nutrients, either as fertilizer or manure, in an effective manner such that crop nutrient needs are met, agricultural yield and profitability are enhanced, and environmental protection and sustainability goals are achieved.

34 Right nutrient source implies matching the fertilizer source and product to crop need and soil properties taking into consideration interactions and balance between nitrogen, phosphorus, potassium and other plant nutrients. Right amount means matching the amount of fertilizer applied to the crop needs in order to avoid adding excess which could lead to loss to the environment. Right time implies making nutrients available only when needed by crops. Right place means placing and keeping nutrients where crops can make use of them (Roberts, 2007).

35 Examples of applicable techniques include the use of soil and plant tissue testing to determine crop nutrient needs, precision agriculture technologies such as canopy sensor-based nitrogen applications and variable rate fertilization for accurate application of crop nutrients and the use of enhanced efficiency fertilizers (EEFs) (technological options for N₂O emission reductions are discussed further in section 4.3.3).

36 Improved irrigation and water saving techniques may increase crop yields and NUE, while reducing N₂O emissions by up to 50% (Scheer et al., 2008; Sanchez-Martin et al., 2010; Kennedy et al., 2013).

37 The use of cover crops following the harvest of the main crop may mop up residual nitrogen from the soil, thereby reducing indirect N₂O emissions as well as improving soil quality (e.g., Bergström and Jokela, 2001; Sperow et al., 2003). However, ploughing cover crops into the soil may increase direct N₂O emissions (Garland et al., 2011).

38 Multiple cropping, including perennial cropping, intercropping and agroforestry systems have the potential to increase biomass yield, reduce leaching and erosion, thereby increasing NUE (Li et al., 2003; Zhang et al., 2003) while decreasing indirect N₂O emissions.

39 Buffer strips slow down runoff thereby enhancing infiltration of nutrients and increasing NUE, which may consequently decrease direct and indirect N₂O emissions (Snyder and Bruulsema, 2007).

40 Conservation tillage reduces erosion and runoff from soil thus reducing indirect N₂O emissions (Snyder and Bruulsema, 2007).

41 Breeding can increase the potential of animals to produce more milk and eggs, and to grow faster, and thereby use the ingested feed and nitrogen more efficiently and reduce the percentage released in dung and urine.

42 Improvements in feed quality and feed management involve (i) using feeds that are easily digested and have a proper energy protein ratio, and (ii) adhering to established nutritional requirements dependent on animal species and growth stage, e.g., implementing phase feeding or rotational grazing.

43 Herd management involves, for example, combinations of appropriate housing and ventilation, disease control and management, fertility control and animal welfare management.

Table 4.3. Estimated relative decrease in N₂O emissions through the implementation of NUE enhancement management practices, in percent (Modified, from Good and Beatty, 2011).

Crop	Decrease in N ₂ O emissions, %	Reference.
America		
Maize	25-40	Mosier et al., 2004; Cassman et al., 2002; Schmidt et al., 2002; McSwiney and Robertson, 2005; Hoben et al., 2011; Ma et al., 2010b
Wheat	28	Matson et al., 1998
Barely	37	Barraclough et al., 2010
Europe		
Wheat	13-20	Sylvester-Bradley and Kindred, 2009; Millar et al., 2010
Asia		
Rice	4-33	Cassman et al., 2003; Wang et al., 2001; Ju et al., 2009; Roy and Misra, 2002
Wheat	61	Ju et al., 2009
Maize	40	Ju et al., 2009

amount of nitrogen excreted per unit animal product by 10 to 30%. However, as in crop production, significant investments in education, training, demonstration and development of site-specific management measures are needed to realize these improvements.

Manure management

The estimated total amount of nitrogen excreted by animals in the world ranges from about 85 to 143 Tg (Oenema and Tamminga, 2005, Davidson, 2009). About half of the urine and faeces (those from grazing animals) are dropped in the field and left unmanaged. The other half is dropped in animal confinement (housing) systems, but less than half of that amount (i.e., 15 to 25% of total nitrogen excreted) is currently collected, properly stored and recycled to agricultural land. However, the ratio of housed animals to grazing animals is increasing because the current expansion of animal production is largely in 'slurry-based, confined animal feeding operations'⁴⁴ (Steinfeld et al., 2010).

Ideally, with proper technology, management and incentives, all manure dropped in animal confinements could be recycled to agricultural land, with only a small fraction of the available nitrogen lost during housing, storage and processing. We estimate that adoption of improved manure management measures, such as improved animal housing⁴⁵ and improved manure storage techniques⁴⁶ (e.g., Rotz, 2004; UNECE, 2013), could increase the fraction of manure nitrogen that is recycled to agricultural land over the next 20 to 40 years from 15-25% to 30-40% of total nitrogen excreted. Additionally, the effectiveness of manure as a fertilizer can be enhanced through the application of the "4R nutrient stewardship" practices discussed earlier. This can double the

effectiveness of the manure nitrogen (relative to fertilizer nitrogen) from the estimated current value of 20-30% to 40-60%⁴⁷ (Schröder, 2005). As a result, the fertilizer nitrogen value of applied manure could be increased from the current 3-8% of total nitrogen excreted (Oenema and Tamminga, 2005) to as high as 12-24% within the next 20 to 40 years. This could lead to a proportional decrease in the amount of synthetic fertilizer needed for crop production thereby decreasing direct and indirect N₂O emissions associated with fertilizers. Increased recycling of manure nitrogen also has the added advantage of reducing ammonia and methane emissions. However, installing a proper manure collection, processing, storage and application system can be costly (e.g., UNECE, 2013) and may therefore require financial incentives for farmers. For hygienic reasons, manure in some countries has to be pasteurized or composted before application to land, which is also costly.

4.3.3. Technological approaches for reducing N₂O emissions from crop and animal production

Emissions of N₂O from agricultural land are dependent on the site and the type of fertilizer applied (Bouwman and Boumans, 2002; Lesschen et al., 2011a). Under well-drained conditions, emissions tend to be lower from nitrate-based fertilizers than from ammonium- and urea-based fertilizers, while the opposite seems true under moist conditions (Tenuta and Beauchamp, 2003; Smith et al., 2013). Some studies have shown greater N₂O emissions with anhydrous ammonia (used in North America) compared with urea (Venterea et al., 2010; Fujinuma et al., 2011). Hence, N₂O emissions can be reduced by choosing a particular fertilizer for a specific location.

44 Animal excrements are collected either as slurries or solid manures (mixed with bedding material). Solid manure in storages is in general a much larger source of N₂O (factor 10 or more) than slurries stored anaerobically (Mosier et al., 1998a). Stable management practices that accumulate a deep layer of litter and that include composting of manure can be large sources of N₂O. Hence, the design of the animal confinement and the manure stores have a large influence on N₂O emissions from manure management.

45 Animal manures and especially slurries contain a relatively large fraction of nitrogen in the form of ammonium, which is rapidly lost to the atmosphere via ammonia volatilization. Decreasing ammonia losses from manures in animal houses requires improved animal housing systems and also low-protein animal feeding (Rotz, 2004; UNECE, 2013).

46 Decreasing ammonia volatilization losses during manure storage requires roofs on top of the storages or decreasing the surface area where losses can take place, and lowering the pH of stored manure (Rotz, 2004; UNECE, 2013).

47 That is, the fertilization effect of 1 kg of nitrogen manure can be increased from its current value of 0.2-0.3 to 0.4-0.6 kg fertilizer nitrogen. Here, we assume also that the expected growth in livestock production between now and 2050 occurs predominantly in slurry-based, improved animal housing systems, where slurries are stored in leak-tight and covered storages, and applied via low-ammonia-emission-application techniques to land.

Another technological option is the use of 'enhanced efficiency fertilizers' instead of conventional fertilizers.⁴⁸ Enhanced efficiency fertilizers have been developed to improve fertilizer efficiency by increasing the availability of nitrogen to crops while reducing nitrogen loss to the environment (Snyder et al., 2009; Zhang et al., 2013) including N₂O emissions (Shoji et al., 2001; Akiyama et al., 2010; Ju et al., 2011). Experiments have shown that these types of fertilizer can decrease N₂O emissions by 35-38%, relative to conventional nitrogen fertilizer (Akiyama et al., 2010). N₂O emission reductions can be further enhanced if site-specific recommendations become available. However, the use of enhanced efficiency fertilizers may increase the cost of fertilizer use by 10% to more than 100%.

N₂O emissions from grazed pastures can be reduced by avoiding animal urine and faeces deposition onto wet soils, taking advantage of the fact that emissions are substantially lower on dry soils than wet soils. Hence, emissions can be reduced by diverting animals onto the drier areas of a field or farm. De Klein et al. (2012) estimated that N₂O emissions may be reduced by 4 to 7 % for every 10% reduction in urine nitrogen deposition onto wet soils.

Emissions of N₂O from grazed pastures can also be reduced by using nitrification inhibitors. Results from 46 studies in New Zealand indicate an average of 57% lower N₂O emissions when the nitrification inhibitor dicyandiamide was applied directly with, or shortly after, urine deposition (de Klein et al., 2011). Studies in Chile indicated an emissions decrease of up to 35% when nitrogen fertilizer and urine were amended with the same chemical (Vistoso et al., 2012; Lanuza et al., 2012). Although nitrogen inhibitors have been shown to be effective in reducing emissions from grazed pastures, they have some practical drawbacks that need to be overcome. First, it is not easy to apply nitrification inhibitors to urine-affected areas in a timely fashion. Second, use of dicyandiamide increases the cost of animal feed production with little or no yield benefit to the farmer. Third, the impacts of inhibitor residues in soil, waters and food have not been sufficiently evaluated. While synthetic chemicals are commonly used as nitrification inhibitors, biological variants are also being studied.⁴⁹

As a final word, scientists are also investigating the possibility of manipulating soil bacteria genetically such that they produce less N₂O (Richardson et al. 2009).

4.4. Co-benefits, success stories and challenges

Apart from reducing N₂O emissions, the four emission reduction strategies discussed above all have potential co-benefits and trade-offs. For example, increasing nitrogen use

efficiency reduces requirements for nitrogen inputs (fertilizer, animal manure, etc.) per unit of product produced, and thereby (other factors remaining the same) lowers ammonia emissions from cropland and its contribution to nitrogen deposition, and decreases the total amount of nitrogen that runs off or is leached from fields. Lower nitrogen runoff and leaching means less frequent eutrophication of lakes and rivers and its impacts (Sutton et al., 2011a, 2013).

Some policies targeted at other environmental problems associated with agriculture have ended up contributing to N₂O emissions reduction. An example is the Nitrates Directive of the European Union, which aims "to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters" (EC, 2013), but has also decreased N₂O emissions from agriculture by up to 10% (Velthof et al., 2013). In the Netherlands, emissions of N₂O from agriculture have decreased by more than 30% between 1990 and 2010, mainly due to the implementation of governmental policies and economic incentives to reduce ammonia emissions and nitrate leaching. These actions have increased nitrogen use efficiency without decreasing productivity (Coenen et al., 2012). Similar experiences have been reported for Denmark (Mikkelsen et al., 2010). However, the economic costs of implementing the various measures are considerable. It must also be noted that some measures aimed at reducing ammonia emissions and nitrate leaching may increase the risk of N₂O emissions (e.g., Smith, 2010; Venterea et al., 2012). This points to the need to make strategies site-specific, and to consider the full nitrogen cycle.

Implementing these emission reduction strategies is not without challenges and barriers. These include: balancing the costs of implementation with returns; the need for guidance and training of farmers; and the need for research to make strategies more site- and farm-specific (Johnson et al., 2007, Smith et al., 2008). In addition, some technical options may not be relevant to small-holder farms that continue to produce the bulk of food in developing countries (UNEP, 2012).

In general, measures specifically to reduce N₂O have not been widely implemented in agriculture. An important factor is probably that N₂O emissions are important globally rather than locally, and therefore farmers are not particularly motivated to address the problem. Also, the lack of a single easy technical fix is a barrier to adopting emission reduction measures. On the other hand, local actions against N₂O emissions in agriculture are critical to lowering global N₂O emissions and protecting the climate system and ozone layer, and these can be supported by national and international policies as discussed elsewhere in this report.

4.5. Estimating emission reduction potential

The business-as-usual scenarios presented in Chapter 3 anticipate that N₂O emissions from global agriculture will increase over the next decades. This is mainly because of increasing demand for food, animal feed and the associated increase in fertilizer nitrogen use and production of manure nitrogen. Here we provide an estimate of possible future N₂O emissions from agriculture under different mitigation scenarios, based on estimated fertilizer nitrogen use and

⁴⁸ Slow-release fertilizer products release their nutrients at a slower rate than conventional fertilizers due to the incorporation of additives that reduce their release. Controlled-release fertilizer products use coatings to delay or extend nutrient release. Stabilized fertilizer products interrupt chemical reactions of nitrogen in the soil in order to prevent losses or emissions to the environment. Nitrification inhibitors are chemicals that inhibit the transformation of ammonium nitrogen into nitrate-nitrogen. All these so-called enhanced efficiency fertilizers have the potential to increase nitrogen use efficiency and have been shown to lower N₂O emissions (Weiske, 2006).

⁴⁹ Recently, *Brachiaria Humidicola*, a tropical forage grass, was reported to exhibit strong nitrification inhibiting properties in its root-exudates (Subbarao et al., 2009). This finding may provide an option for reducing N₂O emissions and nitrate leaching from pastures through biological nitrogen inhibitors (Subbarao et al., 2013).

manure nitrogen production and estimated N₂O emission factors, using the concept of Davidson (2009).

Business-as-usual scenario (BAU)

To estimate the baseline emissions for 2030 and 2050, separate assumptions were made about fertilizer nitrogen use and manure nitrogen production. These projections were derived from Alexandratos and Bruinsma (2012). Multiplying fertilizer nitrogen use and manure nitrogen production by their associated emission factors yields estimates of 6.4 Tg N₂O-N/yr for 2030 and 7.5 Tg N₂O-N/yr for 2050⁵⁰ from the agricultural sector⁵¹ (Table 4.4). Emissions for 2020⁵² are estimated by extrapolation to be 6.0 Tg N₂O-N/yr.

Reduction option 1: Improved efficiency of crop and animal production

Here, the same projections of crop production and animal production from BAU were assumed. For crop production, it is assumed that improved nitrogen use efficiency reduces fertilizer requirements per hectare. Also, the use of enhanced efficiency fertilizers leads to lower N₂O emission factors. For animal production, it is assumed that improved nitrogen use efficiency leads to less manure production per unit of milk, meat and egg produced. These assumptions lead to emissions of 5.2 Tg N₂O-N/yr for 2030 and 4.9 Tg N₂O-N/yr

50 Uncertainty ranges are not provided in the estimation of emission reduction potential because the starting data from Alexandratos and Bruinsma (2012) do not include ranges.

51 In crop production, total projected fertilizer usage in 2030 and 2050 is estimated at 231 and 263 Tg per year respectively (Alexandratos and Bruinsma, 2012). This translates into 132 and 150 Tg per year of fertilizer nitrogen respectively, assuming that fertilizer nitrogen use is 57% of total fertilizer use.

Projections of manure nitrogen production were derived from projections of animal number and animal production reported in Alexandratos and Bruinsma, 2012. Using the projections and considering that cattle produce roughly 60% of total manure nitrogen, we estimate that manure nitrogen production will increase by a total of 35% and 61% between 2005 and 2030 and 2005 and 2050 respectively (that is 1.2% growth per annum between 2005 and 2030 and 0.9% growth per annum between 2030 and 2050). Using 143 Tg N as a base value for total manure nitrogen production for 2005 (Davidson, 2009), we estimate total manure nitrogen production at 193 Tg in 2030 and at 230 Tg in 2050.

Emission factors for fertilizer nitrogen and manure nitrogen were derived from Davidson (2009), but revised (see Chapters 8) because that study used somewhat lower estimates of non-agricultural emissions. The new emission factors are 2.37% and 1.71% for fertilizer and manure nitrogen, respectively. Multiplying fertilizer nitrogen use and manure nitrogen production by the emission factors results in emissions of 6.4 and 7.5 Tg N₂O-N/yr for 2030 and 2050, respectively.

52 All 2020 emissions in the estimation of emission reduction potential were derived by extrapolating the values of 2030 and 2050 assuming a linear relationship.

for 2050 from the agricultural sector (Table 4.4).⁵³ Emissions in 2020 are estimated by extrapolation to be 5.3 Tg N₂O-N/yr.

Emissions reduction option 2: Option 1 plus improved efficiency of manure use

Here, the same assumptions from Option 1 were used, plus it was assumed that the increased recycling of manure from animal production reduces the total fertilizer nitrogen use for crop production⁵⁴. This leads to emissions of 5.0 Tg N₂O-N/yr for 2030 and 4.4 Tg N₂O-N/yr for 2050 (Table 4.4). Emissions in 2020 are estimated by extrapolation to be 5.3 Tg N₂O-N/yr.

Emissions reduction option 3: Option 2 plus reducing food loss and waste

Here, the same assumptions from Option 2 were used, plus it was assumed that food waste is cut by half relative to current estimates and that this leads to a reduction in the fertilizer requirements and manure production. This leads to emissions of 4.6 Tg N₂O-N/yr for 2030 and 3.7 Tg N₂O-N/yr

53 For this scenario, it is assumed that nitrogen use efficiency of crop production increases through a massive implementation in practice of combinations of higher yielding and more efficient crop varieties, improved crop husbandry, use of enhanced efficiency fertilizers and improved nutrient management. In their fertilizer use projections for 2050, Alexandratos and Bruinsma (2012) considered a modest improvement in nitrogen use efficiency of 4% between 2005 and 2030. However, nitrogen use efficiency can be improved by a higher percentage; for example, Cassman et al. (2002, 2003), Doberman and Cassman (2005) and Chen et al. (2011) indicated that nitrogen use efficiency in cereal production could increase by 20 to 50% through a combination of plant breeding, proper technology and incentives (see section 4.3.2). Here, we assumed that the mean nitrogen use efficiency for all crops would increase by 10% in 2030 and by 15% in 2050 relative to the BAU scenario. This will decrease fertilizer use by the same percentage in these years, that is by 14 Tg in 2030 and by 22 Tg in 2050, relative to the BAU scenarios.

For animal production, it is assumed that a combination of animal breeding, use of high quality feed, phase feeding, and improved herd and feed management will increase nitrogen use efficiency in animal production, thereby decreasing nitrogen excretion per unit animal product by 10% in 2030 and by 30% in 2050, relative to the BAU scenario (see section 4.3.2, Bai et al., 2013). This will decrease manure nitrogen excretion from 193 Tg to 174 Tg in 2030 and from 230 to 161 Tg in 2050.

Furthermore, it is assumed that the N₂O emission factor for fertilizer nitrogen would decrease by 15% in 2030 and by 20% in 2050, relative to the values used in the BAU scenario, through the use of enhanced efficiency fertilizers, and that the N₂O emission factor for manure nitrogen will have decreased by 5% in 2030 and by 10% in 2050, relative to the values used in the BAU scenario through the use of nitrification inhibitors (see section 4.3.3). The 'new' emission factors are 2.02% and 1.90% for fertilizer nitrogen in 2030 and 2050, respectively, and 1.62% and 1.54% for manure nitrogen in 2030 and 2050, respectively. Multiplying fertilizer nitrogen use and manure nitrogen production by the emission factors results in 5.2 and 4.9 Tg N₂O-N/yr for 2030 and 2050, respectively.

54 Currently, only 15 to 25% of the total amount of manure nitrogen excreted is effectively collected and returned to crop land, with an estimated fertilizer nitrogen effectiveness value of 20 to 30% (see section 4.3.2). In some countries, animal manures are simply discharged into rivers or stockpiled in lagoons and landfill where the liquids evaporate (Ma et al., 2012). As a result, the estimated fertilizer nitrogen effectiveness value of the total amount of manure excreted ranges between 4 and 11 Tg, with an overall mean of 8 Tg (equivalent to 6% of manure nitrogen excreted). For 2030, we assumed that 30% of manure nitrogen excreted is collected and applied to crop land with an efficiency of 40%, and for 2050 we assumed that 40% of manure nitrogen excreted is collected and applied to crop land with an efficiency of 60%, through a massive implementation in practice of improved animal housing systems, leak-tight manure storage systems, and improved nutrient management (4R-strategy). As a result the fertilizer nitrogen effectiveness value of the manure excreted increases to 12% (30% collected and used with an efficiency of 40%) in 2030 and to 24% (40% collected and used with an efficiency of 60%) in 2050. Hence, the fertilizer nitrogen effectiveness value of the total amount of manure excreted will have increased by 6% in 2030 and by 18% in 2050, relative to the BAU scenario. This would result in a fertilizer nitrogen replacement of 10 Tg in 2030 (6% * 174Tg) and of 29 Tg in 2050 (18% * 161 Tg).

Emission factors for fertilizer nitrogen and manure nitrogen are the same as those in Option 1. Multiplying fertilizer nitrogen use and manure nitrogen production by the emission factors results in 5.0 and 4.4 Tg N₂O-N/yr for 2030 and 2050, respectively.

Table 4.4. Fertilizer nitrogen use and manure nitrogen excretions in 2030 and 2050, and the mean N₂O emission factors (EF), using the concept of Davidson, (2009). Effects of the emission reduction strategies on fertilizer nitrogen use and manure nitrogen excretion were assumed to be additive. See text.

Emission reduction strategy	Nitrogen source	2030			2050		
		N input, Tg	Revised EF	N ₂ O Emissions Tg N ₂ O-N	N input, Tg	Revised EF	N ₂ O Emissions Tg N ₂ O-N
Business-as-usual (BAU)	Fertilizer	132	2.37	3.1	150	2.37	3.6
	Manure	193	1.71	3.3	230	1.71	3.9
Total				6.4			7.5
Option 1: Improving efficiency of crop & animal production	Fertilizer	118	2.02	2.4	128	1.90	2.4
	Manure	174	1.62	2.8	161	1.54	2.5
Total				5.2			4.9
Option 2: Option 1 plus improved efficiency of manure use	Fertilizer	108	2.02	2.2	99	1.90	1.9
	Manure	174	1.62	2.8	161	1.54	2.5
Total				5.0			4.4
Option 3: Option 2 plus reducing food loss and waste	Fertilizer	103	2.02	2.1	89	1.90	1.7
	Manure	156	1.62	2.5	129	1.54	2.0
Total				4.6			3.7
Option 4: Option 3 plus changing diets	Fertilizer	98	2.02	2.0	80	1.90	1.5
	Manure	133	1.62	2.2	97	1.54	1.5
Total				4.1			3.0

for 2050 (Table 4.4).⁵⁵ Emissions in 2020 are estimated by extrapolation to be 5.1 Tg N₂O-N/yr.

Emissions reduction option 4: Option 3 plus changing diets

Here, the same assumptions from Option 3 were used, plus it was assumed that animal production decreases due to a shift away from meat consumption in affluent countries. This leads to emissions of 4.1 Tg N₂O-N/yr for 2030 and 3.0

Tg N₂O-N/yr for 2050 (Table 4.4).⁵⁶ Emissions in 2020 are estimated by extrapolation to be 4.7 Tg N₂O-N/yr.

The measures described above and summarized in Table 4.4 show that fertilizer nitrogen use may decrease by 25% in 2030 and by 47% in 2050, relative to BAU levels (Table 4.4). Similarly, manure nitrogen excretion may decrease by 31% in 2030 and by as much as 58% in 2050, relative to the BAU scenario. Because of the projected decrease in N₂O emission factors, total N₂O emission decrease more than the projected

⁵⁵ Reducing food waste by half from the current estimates of 20 to 40% (see section 4.3.1), would decrease the amount of food required to be produced by the same percentage. This will result in a 5-10% decrease in fertilizer needed for crop production, assuming that half of the food produced is derived from fertilizer nitrogen (Smil, 2000; Erismann et al. 2008). Similarly, the manure nitrogen production would decrease by 10 to 20%, when assuming that the relative waste of plant-derived food and animal derived food is similar. Hence, we assume that fertilizer nitrogen use and manure production would have decreased by 5% and 10% in 2030, and by 10% and 20% in 2050, respectively. As a result, fertilizer nitrogen use would decrease further by 5 Tg to 103 Tg in 2030, and by 10 Tg to 89 Tg in 2050, while manure nitrogen excretion would decrease by 18 Tg to 156 Tg in 2030, and by 32 Tg to 129 Tg in 2050.

Emission factors for fertilizer nitrogen and manure nitrogen are the same as those in Option 1. Multiplying fertilizer nitrogen use and manure nitrogen production by emission factors results in 4.6 Tg and 3.7 Tg N₂O-N/yr for 2030 and 2050, respectively.

⁵⁶ The World Health Organization recommends a daily protein intake of 0.05 kg per capita per day, which translates to about 18 kg per capita per year. WHO also recommends that not more than 50% of the recommended protein intake is animal-derived protein (WHO, 2007). Currently, about 3.5 billion people consume more than 9 kg animal-derived protein per capita per year (range 12-27 kg/capita/yr). In 2030, some 5 billion will consume more than 9 kg animal-derived protein per capita per year (Westhoek et al., 2011). Here, we assume that the affluent half of the world population now consuming an excess amount of proteins in their diet will have reduced their intake of animal-derived protein by 30% in 2030 and by 50% in 2050. As a result, manure nitrogen production would have decreased by roughly 15% in 2030 and by 25% in 2050. This equates to a decrease in manure nitrogen excretion to 133 Tg in 2030 and to 97 Tg in 2050.

Furthermore, currently, 60 to 70% of the utilized agricultural area in the world is used for feed production, including one-third of the cereal area (Steinfeld et al., 2010). If animal production decreases by 15 to 25%, the demand for animal feed also decreases by roughly 15 to 25%. Here, we assume that total fertilizer nitrogen use will have decreased by 5% in 2030 and by 10% in 2050 as a consequence of lower feed needs. As a result, fertilizer nitrogen use will have decreased further by 5 Tg to 98 Tg in 2030, and by 9 Tg to 80 Tg in 2050.

Emission factors for fertilizer nitrogen and manure nitrogen are the same as those in Option 1. Multiplying fertilizer nitrogen use and manure nitrogen production by specific emission factors results in 4.1 and 3.0 Tg N₂O-N/yr for 2030 and 2050, respectively.

decreases in fertilizer nitrogen and manure nitrogen excreted. Total N₂O emissions may decrease by approximately 22% in 2020, 36% in 2030 and 60% in 2050 (Table 4.4). Evidently, these significant reductions can only be achieved with adequate incentives, the help of hundreds of millions of farmers and billions of consumers, and the support of governments and research (see Chapter 8).

4.6. Conclusions

- Agriculture is the main anthropogenic source of atmospheric N₂O. It is in part an inevitable side product of food production due to inefficiencies in the nitrogen cycle.
- N₂O emissions associated with agriculture can be minimized through:
 - a) Increasing nitrogen use efficiency in crop and animal production, including manure nitrogen use efficiency.
 - b) Implementing technology and management practices that decrease the fraction of input nitrogen that is released as N₂O. These include the use of enhanced efficiency fertilizers and nitrification inhibitors in crop production.
 - c) Changing diet and reducing food loss/wastes.
- Total N₂O emissions from the food system can be reduced by up to 60% by 2050 relative to business-as-usual for that year through combinations of these measures.
- Apart from environmental benefits, reducing N₂O emissions from agriculture also yields several health and economic co-benefits.
- Significant investments in education, training, demonstration and development of site-specific technologies are needed to achieve the projected N₂O emission reductions because measures will have to be implemented by billions of consumers and millions of small-holder farmers in the world in site-specific ways.

Chapter 5

Reducing N₂O Emissions from Industry and Fossil Fuel Combustion

Lead Authors: Peter Wiesen (University of Wuppertal, Germany), Timothy J. Wallington (Ford Motor Company, Dearborn, USA), Wilfried Winiwarter (International Institute of Applied Systems Analysis / University of Graz, Austria).

5.1 Introduction

This chapter focuses on N₂O emissions from the combustion of fossil fuels and from the manufacturing industry. It begins with a discussion of their sources of N₂O emissions as well as options for emissions abatement, and then presents estimates of current emissions and trends and N₂O emission reduction potential.

Virtually all combustion processes have N₂O emissions as a by-product. These emissions arise mainly from two pathways. The first pathway is the homogeneous gas-phase reaction⁵⁷ of nitric oxide (NO) with isocyanate (NCO) or imidogen (NH) radicals present in combustion gases (Hayhurst and Lawrence, 1992). The NCO and NH radicals in turn stem from trace amounts of hydrogen cyanide (HCN) and ammonia (NH₃). For N₂O to be produced in these reactions either HCN and/or NH₃ must be present in fuel or they must be generated as the fuel is heated during the combustion process (Hayhurst and Lawrence, 1992). The second pathway involves heterogeneous reactions on, for example, char surfaces during coal combustion and catalyst surfaces in vehicle emission systems.

As we see later in this report, in simple terms N₂O formed in NO_x emission control systems can be viewed as an intermediate in the reduction of NO which escapes the emission control system before complete reduction to N₂ has occurred. A similar principle applies to the main industrial emissions of N₂O. In such systems, N₂O is generally an intermediate in the formation of the intended product. The control of N₂O from these sources is therefore closely linked to efforts to improve efficiency in both NO_x emission control systems and industrial processes.

5.2 Stationary combustion sources

The emissions of N₂O from stationary combustion facilities (public and industrial power plants and other facilities burning fossil fuels) are strongly dependent on

fuel characteristics, the type of combustion technology, the temperature of combustion, and the type of emission control technologies. Thermal decomposition of N₂O is rapid and emissions are negligible for combustion significantly above 1200 K⁵⁸. The N₂O emission rates are highest when combustion temperature is in the range 800 K to 1200 K.

Measurements show that N₂O emissions are low from conventional stationary combustion units, but relatively high from bubbling, re-circulating and pressurized fluidized bed units (De Soete, 1997). The relatively high N₂O emissions from fluidized bed combustors are primarily due to the lower temperature of combustion (800 – 900 K) (Leckner and Åmand, 1992 and refs. therein). Updated estimations of annual N₂O emissions from fluidized bed combustion can be found in Tsupari et al. (2007).

Emission abatement options

The technological options for reducing N₂O emissions from combustion sources include a variety of selective catalytic reduction techniques which can remove up to 80% of emissions (Kanter et al., 2013 and references therein).

Emissions can also be reduced through fuel shifting (for example, a shift from coal to oil or gas would result in lower N₂O emissions) or a reduction in fossil fuel consumption through improving energy efficiency (IEA, 2000; de Jager et al., 2001).

Current emissions, trends and emissions reduction potential

Current global emissions from stationary combustion and transport sources are estimated at around 0.59 (0.4-1.0) Tg N₂O-N/yr (USEPA, 2012). Transport emissions are estimated at 0.115 Tg N₂O-N/yr (see Section 5.3.3). Hence, a best estimate for stationary combustion is 0.48 (0.32-0.80) Tg N₂O-N/yr. Assuming increasing rates of global energy consumption (EC, 2006), baseline emissions (without additional abatement) in 2020 and 2050 are projected to be around 0.55 (0.37-0.93) and 0.87 (0.59-1.46) Tg N₂O-N/yr, respectively.

⁵⁷ Homogeneous reactions are chemical reactions in which the reactants are all in the same phase. One pathway to N₂O formation during combustion occurs when nitric oxide (NO) and isocyanate (NCO) or imidogen (NH) radicals, present in combustion gases react.

⁵⁸ "K" denotes temperature on the Kelvin scale

The current trend to regulate emissions of nitrogen oxides (NO_x) could lead to an increase in N₂O emissions at industrial combustion facilities. This is because NO_x emissions are controlled at lower combustion temperatures, and these lower temperatures increase the rate of N₂O emissions, as noted above. Although N₂O emissions from stationary combustion sources are likely to remain a small percentage of total anthropogenic N₂O emissions, they may nevertheless increase in size for this reason and because of increased capacity of gas turbines for generating electricity.

As stated earlier, N₂O emissions from stationary combustion sources can be reduced by up to 80% through a variety of techniques centering on selective catalytic reduction (Kanter et al., 2013 and references therein). If a robust set of policies were implemented to achieve a 20% adoption of the most effective technologies by 2020 and 60% by 2050, this would achieve an overall reduction of around 16% by 2020 and 48% by 2050. Applying these reduction percentages to the baseline figures above, gives an emission reduction potential of 0.09 Tg N₂O-N/yr (0.06-0.15) in 2020 and 0.42 (0.28-0.71) in 2050, relative to the baseline in these years.

At present, the main barrier to achieving these reductions is that N₂O emissions have not yet been recognized as a problem in this sector. As a result, it does not appear that any country is currently regulating N₂O emissions from stationary combustion sources. However, given the potential for N₂O emission reductions identified here, there is a strong case for giving more attention to mitigation in this sector.

5.3 N₂O emissions from mobile combustion

5.3.1. Vehicular emissions

Light duty vehicles

N₂O emissions from vehicles are small compared to emissions of other air pollutants (Smith and Carey, 1982; Berges et al., 1993; Sjödin et al., 1995). For the small amounts produced, vehicles equipped with 3-way catalysts generally emit more N₂O than vehicles without catalysts (Berges et al., 1993; Dasch, 1992; Hupa and Matinlinna, 1994; Siegl et al., 1996; Sjödin et al., 1995). In this section we consider these N₂O emissions from light-duty gasoline and light-duty diesel vehicles.

The magnitude of N₂O emissions from light-duty vehicles is dependent on the employed emissions control technology and on operating conditions such as fuel sulfur level, driving cycle, ambient temperature, and catalyst operating temperature (Michaels et al., 1998; Odaka et al., 2002; Koike et al., 1999; Baronick et al., 2000; Graham et al., 2009). Estimates from Graham et al. (2009) indicate emission factors of between 14 and 100 µg N₂O/g CO₂⁵⁹ for various types of gasoline and diesel-powered vehicles. CO₂ emissions from the global light-duty vehicle fleet are estimated at

59 Measurements of N₂O emissions were carried out on 200 gasoline and diesel-powered vehicles and the data were combined with those from other studies to create a dataset for 467 vehicles representing a wide range of emission standards. The median emission rates for aged vehicles meeting the progressively more stringent Tier 0 (1981-1993), Tier 1 (1993-1999), low emission vehicle and super ultra-low emission vehicle standards of the United States were 0.242, 0.135, 0.072, and 0.009 g N₂O / liter fuel. This equates to emission factors of 100, 57, 31 and 14 µg N₂O / g CO₂, respectively.

approximately 3 Gt CO₂/yr (WBCSD, 2004). Assuming an emission factor in the range 31-57 µg N₂O/g CO₂ (which is a representative range for the emissions technology of the on-road fleet in 2010), N₂O emissions from the global light-duty fleet will be approximately 0.08 ± 0.03 Tg N₂O-N/yr.

Heavy duty vehicles

The need to meet the increasingly stringent emissions standards for heavy duty diesel vehicles (HDDVs) has led to changes in the implementation of air pollution controls over the last few years⁶⁰. A 2004 estimate of the N₂O emission factor for HDDVs was approximately 3 µg N₂O/g CO₂⁶¹. Using data from Khalek et al. (2009, 2011), the average N₂O emission factors for 2007 and 2010 compliant diesel oxidation catalysts and diesel particulate traps on HDDVs were estimated to be between 27 µg and 100 µg N₂O / g CO₂⁶². These numbers indicate that the emission rate of N₂O has increased because of the advanced emission control systems used in modern HDDVs. Adopting an emission factor of between 3 and 27 µg N₂O g/CO₂ for the on-road fleet in 2010, and considering that CO₂ emissions from the global HDDV fleet in 2010 were approximately 1.5 Gt/yr (WBCSD, 2004) yields emissions from the global HDDV fleets of approximately 0.015 ± 0.012 Tg N₂O-N/yr.

Current emissions and trends

Emissions from on-road vehicles (light-duty and heavy-duty) in 2010 are estimated to be 0.095 ± 0.042 Tg N₂O-N/yr. To roughly estimate the 2020 and 2050 emissions from light-duty vehicles, the proportional correlation between N₂O emissions and volatile organic compound (VOCs) emissions, as noted by Graham et al. (2009), was used. Global VOC emissions from light-duty vehicles are expected to decline by approximately 60% and 90% by 2020 and 2050, respectively, relative to 2010 (WBCSD, 2004). Hence, N₂O emissions are estimated to be 0.03 ± 0.02 Tg N₂O-N/yr in 2020 and 0.010 ± 0.004 Tg N₂O-N/yr in 2050 for light-duty vehicles. At present, it is unclear how the new emissions control technology for heavy-duty diesel vehicles introduced in 2010 will be further modified, how and when this technology will be taken up by the global fleet, or how N₂O emissions might change as a result. Hence, to estimate emissions in 2020 and 2050, emissions in 2010 were simply scaled up by 136% and 211% reflecting the projected increase in transport energy use to give 0.020 ± 0.016 Tg N₂O-N/yr and 0.032 ± 0.025 Tg N₂O-N/yr. Total emissions from the combined light-duty and heavy-

60 Prior to 2004, heavy duty diesel vehicles (HDDVs) were not equipped with catalyst-based emissions control technology. To meet the increasingly stringent emissions standards, catalyst-based technology has been added to HDDVs over the past decade; in 2004 diesel oxidation catalysts were added and later in 2007 diesel particulate traps were further added. The selective catalytic reduction technology was then added in 2010.

61 This is based on USEPA (2004) which estimates N₂O emissions from HDDVs at approximately 0.003 g/km and CO₂ emissions from HDDVs at approximately 1000 g/km. Hence the N₂O emission factor was approximately 3 µg N₂O/g CO₂

62 Estimates for 2007 compliant vehicles were calculated from N₂O and CO₂ data for 18 different vehicle/test combinations as reported by Khalek et al. (2009), while that for 2010 compliant vehicles were calculated from information presented in Khalek et al. (2013), which states that CO₂ emissions from three 2010 compliant HDDVs are approximately 3% lower than values for 2007 compliant vehicles (i.e. approximately 600 g CO₂ per brake horse power hour) and N₂O emissions were approximately 70-75 mg per brake horse power hour.

duty road fleet are therefore projected as 0.050 ± 0.036 Tg N_2O -N/yr in 2020 and 0.042 ± 0.029 Tg N_2O -N/yr in 2050.

This sector is already showing declining N_2O emissions per vehicle mile, especially from light-duty vehicles, reflecting lower emissions from newer vehicles and fleet turn-over⁶³ (Wallington et al., 2008; EIA, 2011; USEPA, 2012). The main barrier to further reductions is the ongoing growth in the global vehicle fleet, which could offset the gains of improved technical efficiency.

5.3.2. N_2O emissions from aircraft

Based on very limited data, current N_2O emissions from aviation are estimated to be around 0.020 ± 0.005 Tg N_2O -N/yr.⁶⁴ Baseline emissions of N_2O in 2020 are estimated to be slightly higher at 0.030 ± 0.005 Tg N_2O -N/yr.⁶⁵ Using the emission reduction potential of 0.1 Gt CO_2 for 2020 (UNEP, 2011), gives a reduction potential for N_2O of around 0.003 Tg N_2O -N/yr. Even if CO_2 emissions from aviation grow by 2050 between a factor of 2.0 and 3.6 (Owen et al, 2010), the global N_2O emissions from aviation will still be very low if they maintain their current proportion to CO_2 emissions.

5.3.3. Estimating future N_2O emissions from the transport sector

Summing the contributions from road transportation and aircraft, total N_2O emissions from the transportation sector come to 0.115 ± 0.047 Tg N_2O -N/yr in 2010; 0.090 ± 0.046 Tg N_2O -N/yr in 2020; and 0.082 ± 0.047 Tg N_2O -N/yr in 2050. These baseline estimates show a decrease in emissions from the 2010 value by approximately 20% in 2020 and 30% in 2050. The emissions from the transport sector are currently low and are decreasing mainly as a result of the diffusion of more efficient emissions control technology for road vehicles mandated by regulations focused on NO_x and VOC control. There appears to be little additional scope for further reductions in N_2O emissions from the transport sector over those noted above.

5.4 N_2O emissions from industrial processes

5.4.1. N_2O from nitric acid production

Industrial emissions of N_2O come mainly from two manufacturing processes: nitric and adipic acid production. Nitric acid (HNO_3) is a key ingredient in some nitrogen-based fertilizers and is also used for the production of adipic acid, explosives, and metal etching, as well as in the processing of ferrous metals. More than 80% of the world nitric acid production goes into the production of ammonium nitrate and calcium ammonium nitrate. About three quarters of the ammonium nitrate produced is used for fertilizers and one-quarter for various industrial applications (IHS, 2013). The entire production of nitric acid takes place at around 500 to 600 plants worldwide (Kollmuss and Lazarus, 2010).

63 This decrease is predominantly in OECD and EU countries.

64 This assumes an emission factor of $47 \mu\text{g N}_2\text{O/g CO}_2$ (based on Wiesen et al., 1994, 1996; consistent with Heland and Schäfer, 1998) and CO_2 emissions from aviation of 0.7 Gt CO_2/yr (UNEP, 2011). The UNEP reference gives baseline emissions in the aviation sector of 0.74 Gt CO_2 -equivalent/yr. A rounded figure of 0.7 Gt CO_2/yr is used here assuming that nearly all of the CO_2 -equivalent emissions are made up of CO_2 .

65 Assuming uncontrolled emissions of CO_2 of about 0.8 to 1.0 Gt from UNEP (2011) and an emission factor of $47 \mu\text{g N}_2\text{O/g CO}_2$

Nitric acid production involves the oxidation of ammonia using a platinum catalyst in the Ostwald process. Nitrous oxide is released as a by-product of this process. Emission rates depend on operating conditions at the facility (e.g. operating pressure), catalyst type and age, nitric acid concentration and the type of abatement technology applied.

Emission abatement technologies

Nitric acid plants now represent the single largest industrial source of N_2O and so there has been strong interest in technologies to lower these emissions. The installation of N_2O abatement technologies in nitric acid plants became commercially attractive in the European Union with the onset of the emissions trading system as of 2013 (Ecofys/Fraunhofer Institute/Okon-Institut, 2009). In the US, 20% of nitric acid plants are currently equipped with some type of NO_x abatement equipment, which also reduces N_2O as a side benefit (USEPA, 2006).

In principle, there are several different ways to control N_2O emissions from this source. The nitric acid industry in the US uses both selective (SCR) and non-selective catalytic reduction (NSCR). While NSCR is more effective than SCR at controlling N_2O , these units are generally not used in current facilities because of their high energy costs. Recently, progress has been made in reducing N_2O released from the NH_3 oxidation process by using more efficient oxidation conditions with lower reaction temperatures.

Abatement of N_2O and NO_x emissions in nitric acid plants can also be accomplished by using an iron zeolite catalyst. The catalyst either decomposes N_2O into N_2 and O_2 (an effect, which increases significantly in the presence of NO_x in the exhaust gas) or reduces N_2O using various reducing agents such as hydrocarbons. In addition, the iron zeolites allow N_2O and NO_x abatement to be combined. Several nitric acid plants have been equipped with these systems, which achieve N_2O removal rates of 98-99% with NO_x emission levels also being reduced (Groves and Frank, 2009).

Kollmuss and Lazarus (2010) evaluated industrial nitric acid projects under the Clean Development Mechanism (CDM) and concluded that the risk of carbon leakage⁶⁶ is unlikely for these projects. The authors also provided detailed recommendations on how the current nitric acid methodologies could be improved and simplified through the use of a common benchmarking approach leading to a further reduction of N_2O emissions from nitric acid production.

Current emissions, trends and emission reduction potential

Some recent estimates of N_2O emissions from industrial processes do not distinguish between emissions from nitric acid and adipic acid manufacturing (e.g., USEPA, 2012; JRC, 2013). USEPA (2012) estimated current (2010) worldwide emissions of N_2O from industry at 0.24 Tg N_2O -N/yr. However, detailed data available on emissions from adipic acid plants point to a capacity and emissions increase in China after 2006 which presumably was not included in

66 Carbon leakage means that there is an increase in greenhouse gas emissions (here: N_2O) in one country as a result of an emission reduction by a second country with a strict climate policy.

the USEPA (2012) estimates⁶⁷ (see Section 5.4.2). Hence, to estimate 2010 N₂O emissions from nitric acid plants, the total emissions from adipic acid plants existing before 2008 (0.04 Tg N₂O-N/yr – see Section 5.4.2) were subtracted from the USEPA (2012) estimate of 0.24 Tg N₂O-N/yr to arrive at 0.20 (0.13-0.40) Tg N₂O-N/yr.

As demand for fertilizer and industrial products grows over the coming decades, baseline emissions of N₂O from nitric acid production are also expected to grow. Assuming that the relative contribution of nitric acid to industrial emissions of N₂O remains the same, USEPA (2012) estimates growth rates of 1.5% annually from 2015 (after a stagnation period between 2010 and 2015). This translates to a projected 7% and 24% growth up to 2020 and 2030, respectively. Emissions from nitric acid production could therefore grow to 0.21 (0.14-0.43) and 0.25 (0.17-0.50) Tg N₂O-N/yr in 2020 and 2050 respectively. Extrapolating from these trends and assuming further growth at 1% per annum will yield a 50% production increase by 2050. Hence, business-as-usual emissions from this sector would be 0.30 (0.20-0.61) Tg N₂O-N/yr in 2050.

Relative to 2020 and 2030 baseline emissions, the maximum technical emission reduction potential in the nitric acid production sector is around 48% and 71% for these years respectively⁶⁸. This is equivalent to emission reductions of 0.10 and 0.18 Tg N₂O-N/yr, respectively. By 2050 the maximum technical emissions reduction potential could reach 90%⁶⁹, equivalent to an emissions reduction of 0.27 Tg N₂O-N/yr relative to the 2050 baseline.

5.4.2. N₂O from adipic acid production

Adipic acid production is the second important industrial source of N₂O emissions. Adipic acid (CH₂)₄(COOH)₂, is a major input to nylon production, and is used for manufacturing carpets, clothing, tires, dyes and insecticides. N₂O emissions arise as an unintended by-product during the oxidation of a ketone-alcohol mixture with nitric acid.

According to Schneider et al (2010), there are only about two dozen adipic acid plants in the world. The largest production takes place in the US, EU and China, which together account for 70% of the worldwide N₂O emissions from this sector (USEPA, 2006).

Emissions abatement technologies

The most common approaches to abating N₂O emissions in this sector are catalytic decomposition and thermal destruction. These methods convert N₂O into elemental nitrogen (N₂) and oxygen. N₂O can also be recycled as feedstock for nitric or adipic acid production. In addition, another abatement process under development consumes N₂O as an oxidant for phenol synthesis (Shimizu et al., 2000, and references therein). These authors give a detailed

description of the technology for each adipic acid producing company that has been made public through their patent applications.

Generally, for adipic acid production, N₂O emission reduction is estimated to have improved from approximately 32% in 1990 to approximately 90%. Current abatement technologies allow N₂O emissions in the exhaust to be reduced up to 99% (Schneider et al., 2010), but this does not include emissions that occur during service intervals of the abatement equipment⁷⁰. This can however be addressed by installing a second N₂O abatement device which could result in almost zero N₂O emissions (SEtatWork, 2009).

An evaluation by Schneider et al (2010) shows that approximately 70% of the existing and operating adipic acid plants already have abatement technologies installed, either voluntarily or under the Clean Development Mechanism (CDM) or the Joint Implementation (JI) programme⁷¹. The evaluation concluded that the CDM has been effective in reducing N₂O emissions but also indicated that CDM projects have probably also caused carbon leakage, particularly during the economic crisis in the years 2008 and 2009⁷². This amount was equivalent to about 13.5 Mt CO₂. It follows that future N₂O emissions reduction projects need to take this into consideration. Options for avoiding carbon leakage, according to Schneider et al., include revision of the baseline and monitoring methodology, exclusion of adipic acid plants from the CDM, restrictions on the use of CERs from adipic acid projects or sectoral emissions trading.

Current emissions, trends and emission reduction potential

Estimating current emissions of N₂O from adipic acid manufacture clearly needs to consider the abatement devices installed. In some countries, such as the US, emission controls have led to a sharp decrease in N₂O emissions over the last two decades (Figure 5.1). Some industry sources suggest that nearly all new adipic acid producers install N₂O abatement technologies (Wiesen, 2010). Detailed accounting by plant (Schneider et al., 2010) indicates that about 20% of the overall production capacity nevertheless operates without abatement. Interestingly these are mostly modern plants in China that started operation in 2008 or 2009 and which are too new to be eligible for CDM projects. There seems to be no technical reason for not installing abatement technologies apart from the cost.

Current global emissions of N₂O from adipic acid manufacturing have been estimated to be one third of industrial emissions (USEPA, 2006). This however comes with considerable uncertainty regarding the degree of emission abatement already implemented; hence a bottom-up approach was used here to estimate 2010 global N₂O emissions from adipic acid plants.

67 The USEPA (2010) figures indicate a decrease in emissions from adipic acid since the earlier publication in 2006 (USEPA, 2006), instead of the increase that probably occurred because of new plants (without abatement technology) in China after 2006.

68 This is based on the assumption that by 2020 and 2030, 50% and 75% respectively of all nitric acid plants are equipped with best available technology for N₂O emissions removal and that this technology achieves a reduction of 95% of uncontrolled emissions on average. This equates to a net emission reduction of 48% in 2020 and 71% in 2030.

69 If 95% of all nitric acid plants are equipped with best available technology that achieves 95% emission reduction.

70 N₂O formed during the service of the N₂O abatement facility is usually released into the atmosphere unabated

71 JI projects allow a country with an emission reduction or limitation commitment under the Kyoto Protocol (Annex B Party) to earn emission reduction units (ERUs) from an emission-reduction or emission removal project in another Annex B Party. Each ERU is equivalent to one tonne of CO₂ and can be counted towards meeting its Kyoto target

72 In other words, controlling N₂O emissions resulted in a shift of adipic acid production partially from plants, which installed abatement technology in the 1990s, to CDM plants. A contrary view has been expressed regarding this claim. See <http://cdm.ccchina.gov.cn/WebSite/CDM/UpFile/File2525.pdf> and <http://cdm.ccchina.gov.cn/WebSite/CDM/UpFile/File2546.pdf>

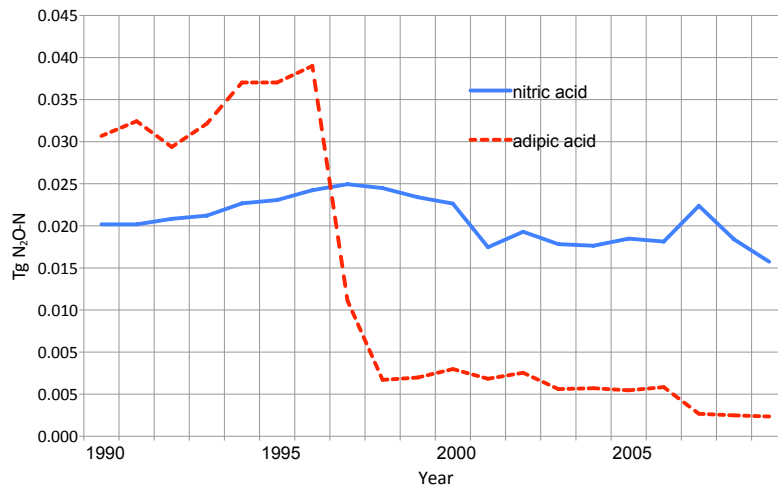


Figure 5.1: US nitrous oxide emissions from nitric acid and adipic acid production. Source: US Energy Information Administration (http://www.eia.gov/environment/emissions/ghg_report/).

Using the list of all existing adipic acid plants in Schneider et al. (2010), global 2010 emissions were estimated as 0.12 (0.05-0.20) Tg N₂O-N/yr⁷³. The estimation shows that almost two thirds (0.07 Tg N₂O-N/yr) comes from new plants in China (mentioned earlier), which do not have emissions abatement equipment. As this increase in emissions since 2008 was apparently not incorporated in reports up to now (including USEPA, 2012), we assume that these reports have not considered the new emission sources and have only accounted for emissions from older plants (estimated as 0.04 Tg N₂O-N/yr using the bottom-up approach). It should be noted, however, that this discrepancy obviously increases the uncertainty of estimates.

Projections of future emissions from this sector must take into account the likelihood of increased adipic acid production as a consequence of growing global demand for nylon (especially in carpets) and plastics. Using the USEPA (2012) projections and assuming no implementation of additional abatement, baseline emissions would increase by 7% in 2020 and by 24% in 2030 (similar to the projections for nitric acid production). Using these estimates and again assuming a 50% increase by 2050, then baseline emissions would be approximately 0.13 (0.05-0.22) in 2020, 0.15 (0.06-0.25), in 2030, and 0.18 (0.07-0.31) Tg N₂O-N/yr, in 2050. This assumes that 20% of adipic acid plants remain unabated, which of course depends very much on incentives and other factors influencing the adoption of abatement equipment.

With many plants already having abatement technology installed, additional emission reduction potential consists of (i) expanding coverage to the remaining 20% of capacity, which we assume can be achieved by 2020, and (ii) a gradual installation of improved equipment in existing and new plants that would further extend emission reductions from 95% to 99% (see above). It is estimated that the remaining emission reduction potential in the adipic acid sector from these two activities could be 84% or 0.11 Tg N₂O-N/yr in 2020 and 89% or 0.13 Tg N₂O-N/yr in 2030 relative to baseline for these

years.⁷⁴ By 2050, the maximum technical emission reduction potential could reach 95%, equivalent to a reduction of 0.17 Tg N₂O-N/yr relative to the 2050 baseline⁷⁵.

5.4.3. Towards reducing N₂O emissions in the industrial sector

The two industries just described – adipic acid and nitric acid production – account for around 5% of gross global anthropogenic N₂O emissions. Considering the limited number of production plants involved, and the wide availability of abatement technologies, emission reductions might be easier to achieve here than in sectors having many diffuse emission sources such as in the biomass burning and agriculture sectors.

Significant progress has already been achieved in reducing emissions from adipic acid plants with approximately 70% of existing plants (as of 2010) already having N₂O abatement technologies. Not as much progress has been made in controlling N₂O from nitric acid plants. As an example, Figure 5.1 shows that substantial progress has been made in reducing emissions from adipic acid plants in the United States, but only modest progress in the nitric acid manufacturing sector. The nitric acid plants in developing countries with N₂O abatement technology appear to be supported by the Clean Development Mechanism of the Climate Convention (Kollmuss and Lazarus, 2010). These authors also reported that, as of 2010, regulations controlling N₂O emissions from nitric acid plants were rare in developed countries and absent in developing countries.

In general, N₂O abatement in nitric acid plants is still only rarely implemented and happens in most cases only under some form of incentive, such as offset programs or emissions trading systems. But progress in reducing N₂O from nitric acid production might be accelerated by transferring some of the successful experience gained in reducing N₂O from adipic acid production.

73 All existing adipic acid plants listed in Schneider et al (2010) were separated into abated and unabated plants and old and new plants. N₂O emissions were then derived for each plant using the IPCC default emission factor (IPCC 2006) and the capacities of the plants, with the assumption that the plants were operating at 90% of their stated capacities.

74 This assumes that by 2020 and 2030, 30% and 60%, respectively, of all adipic acid plants will be equipped with best available technology for N₂O emission removal, and that this technology achieves a reduction of 99% of uncontrolled emissions on average. It also assumes that 20% of adipic acid production, which is still unabated in the baseline, will be at a minimum, equipped with devices that reduce N₂O emissions on the average by 95%.

75 If 95% of all adipic acid plants are equipped with best available technology achieving 99% removal of uncontrolled N₂O emissions, while all remaining plants at least achieve 95% removal.

While the cost of installing abatement technologies could be a possible barrier to reducing N₂O emission in adipic and nitric acid plants, incentives such as the CDM, JI and the EU-Emissions Trading System (EU-ETS) have helped increase the rate of adoption of abatement technologies⁷⁶. Also, a public-private partnership could accelerate the uptake of N₂O controls in these plants.

5.5 Conclusions

- N₂O emissions from combustion and industrial sources are small compared to agriculture, but offer key opportunities for significant emission reductions.
- Until now, stationary combustion has not been a major focus of N₂O mitigation. However, technologies and practices are available for this sector that could reduce emissions by 0.09 Tg N₂O-N/yr in 2020 and 0.42 Tg N₂O-N/yr in 2050, relative to the baseline emissions in these years.
- Emissions from the mobile combustion sector (road and air transport) are currently small and are projected to decline by approximately 20% in 2020 and 30% in 2050 relative to emissions in 2010 as a side effect of controlling other air pollutants.

⁷⁶ Kollmuss and Lazarus (2010) stated that except for a few pilot projects in Europe, N₂O abatement was not practiced before the implementation of CDM, JI and the EU-ETS. New N₂O abatement technologies and monitoring standards were introduced in 63 plants in 11 Non-Annex-1 countries with CDM support.

- Techniques to reduce N₂O emissions from nitric acid plants with N₂O removal efficiency of 98-99% are available. However, these techniques are yet to be widely implemented. Implementing these technologies could potentially decrease N₂O emissions by 0.10 Tg N₂O-N/yr and 0.27 Tg N₂O-N/yr in 2020 and 2050 respectively, relative to baseline emissions in these years.
- N₂O emissions from adipic acid production have already been significantly reduced because of the wide adoption of abatement techniques. This is an example of how quick implementation of abatement techniques can lead to significant emission reductions. However, emissions can be further reduced from this sector by adopting advanced abatement technologies and by increasing the number of plants with pollution control equipment. Implementing these steps could reduce emissions by 0.11 Tg N₂O-N/yr in 2020 and 0.17 Tg N₂O-N/yr in 2050 relative to baseline emissions in these years.

Chapter 6

Reducing N₂O Emissions from Biomass Burning in Landscape Fires and Household Stoves

Lead Author: Guido R. van der Werf (VU University Amsterdam, The Netherlands),

Contributing Authors: C. P (Mick) Meyer (CSIRO Marine and Atmospheric Research, Australia), Paulo Artaxo (University of São Paulo, Brazil)

6.1. Introduction

This chapter describes N₂O emissions from two main categories of biomass burning – landscape fires and household biomass stoves. Biomass burning occurs throughout the world whenever dry biomass and an ignition source come together. Earlier, fires were started mostly by lightning but nowadays the majority of fires are thought to be ignited by humans (USEPA, 2010). This is particularly the case in tropical savannahs and forests. But even in boreal and temperate regions, fire frequency is highest near human settlements and roads. Nevertheless, the increase in ignition frequency has not necessarily led to an increase in emissions. This is because the landscape fragmentation associated with human settlements limits fire size. Also, land uses such as agriculture often exclude parts of the landscape from burning. This is especially the case in tropical savannahs. Besides landscape fires, the burning of biomass in households mostly for cooking and heating purposes is an important source of N₂O emissions.

6.2. N₂O Emissions from biomass burning

In landscape fires, the amount of N₂O emitted depends on the extent of fires, biomass density, combustion completeness⁷⁷, and other factors represented by an “emission factor”. The emission factor indicates how much N₂O is emitted per unit dry matter combusted and depends on the nitrogen content of the fuel and burning characteristics.

Emissions from landscape fires are computed as part of the Global Fire Emissions Database (GFED) (Figure 6.1). Calculations are based on burned area estimates from satellite observations (Giglio et al., 2010), estimates of biomass and combustion completeness from a biogeochemical model (van der Werf et al., 2010), and emission factors estimated by Andreae and Merlet (2001).

Over the period 1997-2011, mean annual landscape fire emissions were estimated to be about 0.6 Tg N₂O-N/yr (Table 6.1). Around 85% are emitted in the tropics, mostly from savannahs, grasslands, and woodlands, although clearing of tropical rainforest for agriculture and the burning of agricultural waste is also significant. Africa is the most important continent (around 50% of total global emissions), mostly due to savannah fires. Savannah fires are also very important in Australia.

Fires in temperate and boreal forests are responsible for 15-20% of the global budget as are fires in tropical forests. Smaller contributions come from tropical peat fires (mostly in Indonesia) and from the burning of crop residues in agricultural lands. However, agricultural residue fires are small in size and therefore difficult to detect by satellite. Consequently, their emissions tend to be underestimated in the GFED. Hence, the estimate of agricultural residue burning in Table 6.1 is based instead on survey data of crop residue fires from Yevich and Logan (2003).

On the global scale, no trends have emerged from the satellite record which now spans about 15 years. Furthermore, it is difficult to assess a change in frequency and scope of future landscape fires. Therefore, baseline emissions for 2020 and 2050 are assumed to be the same as current rates.

In many parts of the world, stoves fired by biomass are used for household cooking and heating. Fuel wood is the most important source of biomass, but charcoal, dung, and crop residues are also used. N₂O emissions from these fires are more difficult to estimate than from landscape fires as they cannot be detected by satellite. The most recent estimates of total biomass burned in household stoves is 2460 Tg in year 2000 (Fernandes et al., 2007). Combining this information with emission factors from Andreae and Merlet (2001) yields an estimate of 0.15 Tg N₂O-N emitted per year (Table 6.1).

⁷⁷ Combustion completeness is defined as the fraction of fuel load that is actually combusted.

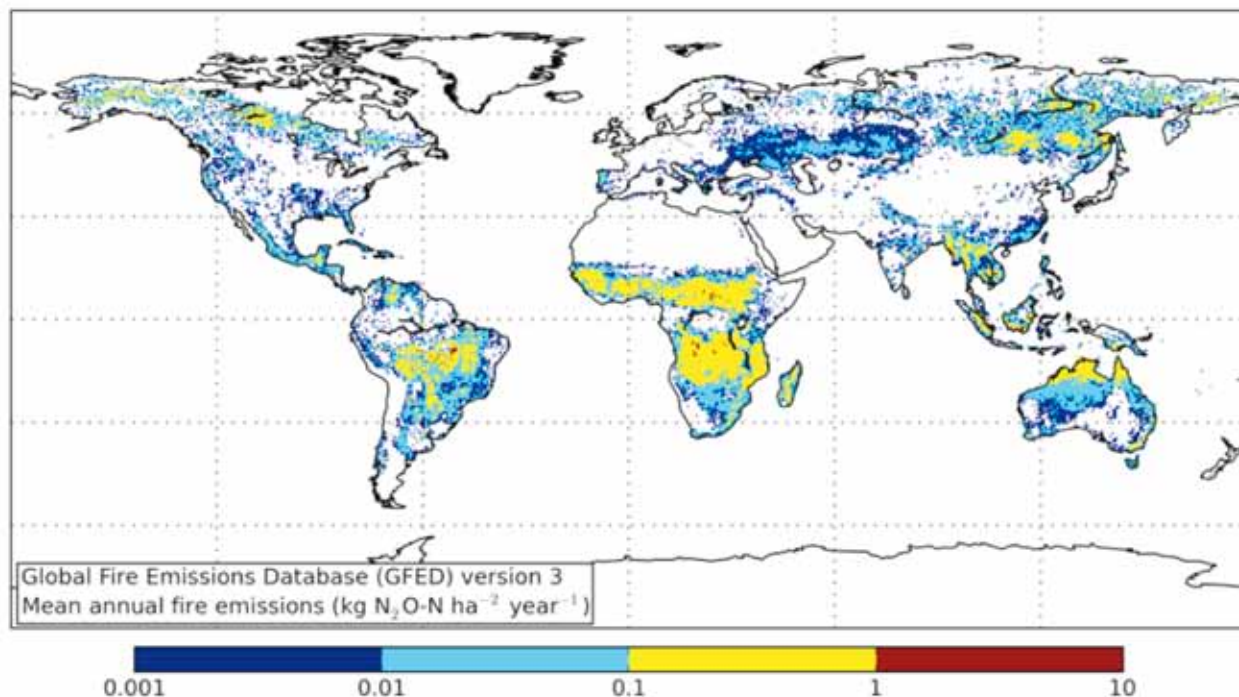


Figure 6.1: Landscape fire N₂O emission estimates based on satellite-derived burned area and biogeochemical modeling. Based on Giglio et al. (2010) and van der Werf et al. (2010).

Table 6.1. Current emissions for various biomass burning categories using several estimates of biomass burned explained in the footnotes, and emission factors from Andreae and Merlet (2001). Baseline emissions for 2020 and 2050 are assumed to be similar to current rates.

Source	Current emissions in Tg N ₂ O-N/yr (Various time periods. See footnotes).
Savannah fires	0.32 ¹
Tropical forest fires (deforestation)	0.10 ¹
Temperate and boreal forest fires	0.10 ¹
Tropical peat fires	0.02 ¹
Agricultural waste burning (crop residue)	0.04 ²
Total from landscape	0.58
Household biomass stoves ³	0.15
Total	0.73

¹ Average for the 1997–2011 period based on GFED dry matter emissions

² For the year 1985, based on Yevich and Logan (2003)

³ For the year 2000, based on Fernandes et al. (2007)

6.3 Options for emission reductions

6.3.1. Options for reducing emissions in landscape fires

Although landscape fires are a natural phenomenon, humans have modified the frequency and extent of these fires in many parts of the world. The degree to which N₂O emissions from landscape fires can be reduced depends in large part on the relative importance of humans versus nature in starting these fires. This varies between biomes and regions. To broadly assess mitigation options, three classes of fire regimes can be distinguished – anthropogenic fire regimes, natural fire regimes, and natural fire regimes modified by humans. They are explained below and summarized in Table 6.2 along with their potential mitigation options.

Anthropogenic fire regimes

Because fire is a cheap and efficient tool for clearing fields, it is widely used in agriculture to remove stubble prior to sowing or a fallow period, or to clear forest for crops or pasture. The burning of agricultural crop residues is subject to air quality regulations in some regions, mostly to reduce impacts from particulate matter pollution. In such regions, agricultural waste is not burned but chipped, shredded, mulched, or used as composting waste. Exporting this approach to other regions would therefore lower emissions, keeping in mind that some of the nitrogen contained in these wastes is ultimately returned to the atmosphere as N₂O through mineralization and denitrification during composting. Nevertheless, substituting the burning of waste with composting generally reduces emissions (Davidson et al., 2008; Cook and Meyer 2009).

Emission reductions can also be achieved by lessening the use of fires to clear forests (as part of the deforestation process). As noted, fires are routinely used as a clearing tool during the dry season in preparation for agriculture. To maximize the emission reduction potential, it is important that the use of fire is also minimized after forest clearing (Aragao and Shimabukuro 2010). Tropical peat fires (mostly in Indonesia) can also be reduced by rewetting previously drained peatlands and by discouraging the use of fire to clear land.

Natural fire regimes

While wildfires are often considered disasters, they are also sometimes a prerequisite for the sustenance of an ecosystem. For example, species composition and regeneration in boreal forests, Eucalyptus forests, and savannahs are dependent on fire. This is particularly important in temperate and boreal forests where large fires are usually ignited by lightning. These fires may increase in extent and severity under climate change due to warmer and drier conditions (Flannigan et al.,

2013; Westerling et al., 2006), potentially offsetting some of the emission reductions discussed elsewhere in this chapter.

On the other hand, wildfires also pose a threat to human settlements and have therefore traditionally been controlled. This has led to the unnatural and excessive build up of combustible vegetation, resulting in extremely destructive wildfires that cannot be controlled. But fire management strategies are now shifting since it has been recognized that active suppression of all fires is often counterproductive.

One way to reduce the destructiveness of fires is by “fuel reduction”, also known as “prescribed burning”. This is a practice by which forest vegetation is burned early in the fire season when fires tend to spread more slowly because of cooler and more moist conditions. The aim is to reduce the amount of burnable vegetation and thereby reduce the severity and/or frequency of wildfires. Prescribed burning has been practiced for millennia and is now recognized as a way to lower the risks of uncontrolled wildfires. However, this approach has drawbacks, among which may be a more frequent exposure to smoke.

Natural fire regimes modified by humans

This category includes mostly savannah fires which are responsible for around 50% of N₂O emissions from all landscape fires. Savannahs have distinct dry and wet seasons. Fires occur during the dry season, and mostly consume only grass, leaf litter and low shrubs which regrow during the following wet season. Assuming a stable fire regime, the amount of vegetation burned is about equal to the amount regrown, implying that savannah systems tend to be CO₂ neutral over decades (Cook and Meyer, 2009). Since most trees here have a thick bark protecting them from fire, savannah fires tend to be low in intensity in comparison to forest wildfires, and tree canopies are rarely destroyed. But they occur with a high frequency, i.e. every 1 to 5 years.

In tropical savannahs, the distinct seasonality, relatively constant rates of fuel production, and high rates of litter decay related to high ambient temperatures offer great potential for reducing N₂O emissions from fires. Strategies for reducing emissions, mostly tried out in Australia (see Section 6.4), focus on two areas: reducing fire frequency and adjusting fire seasonality.

Because fuel accumulation rates decline with time since the last fire, *reducing fire frequency* has the effect of shifting the pathway by which fuel carbon is returned to the atmosphere. Reducing fire frequency reduces the fraction of vegetation burnt and increases the fraction that decays,

resulting in lower overall emissions of N₂O and CH₄. An extreme variant of this approach is to exclude fire completely, which could ultimately change a savannah to a forest.

The second strategy is *adjusting the fire seasonality* of savannahs. Under normal circumstances fires occur at an increasing rate during the dry season and cover a wide continuous area in which much of the combustible material is completely consumed by fire (Figure 6.2, right photo). “Adjusting the fire seasonality” in this case means introducing prescribed burning early in the dry season, and encouraging more patchy fires with a lower fraction of combustible material being burned (Figure 6.2, left photo). This type of prescribing burning burns much less fuel carbon and produces proportionately fewer greenhouse gas emissions as compared to the usual fire regime.

6.3.2 Options for reducing emissions from household biomass stoves

One way to reduce N₂O emissions from household biomass stoves is to improve their fuel and combustion efficiency. Several stove types consume less fuel wood than simple open fires or traditional cook stoves, and produce proportionately fewer emissions. An example is given in Section 6.4.

Another option is to change the fuel source, for example, by switching from wood fuels to liquefied petroleum gas. Although the latter fuel produces CO₂, its net effect on greenhouse gas emissions can be lower than that of wood combustion for an equivalent task, when all products of incomplete combustion are considered (Smith et al., 2000).

A side benefit of improving the efficiency of stoves or switching the fuels they use is that these measures tend to produce less smoke than traditional biomass cook stoves and thereby reduce exposure to dangerous indoor air pollution (e.g., WHO, 2006). Another side benefit is that these actions tend to reduce emissions of black carbon – a contributor to climate change (UNEP/WMO, 2011; UNEP 2011).

6.3.3. Co-benefits and barriers

As noted above for improved household stoves, each of the mitigation options described above has important co-benefits. For example early-season prescribed burning not only reduces N₂O and other emissions but also helps to conserve biodiversity. Other co-benefits of mitigation actions are summarized in Table 6.2.

Despite the fact that mitigation options bring climate protection and many other co-benefits, there are many



Figure 6.2: Early (left) and late (right) season burning in an Australian savannah. Copyright Garry Cook, CSIRO

Table 6.2. Options, co-benefits and barriers to N₂O mitigation for various fire types

Biomass burning category	N ₂ O emission mitigation option	Main co-benefits	Barriers and drawbacks to implementation
Savannah and pasture fires	Early season prescribed burning	Biodiversity conservation	Uncertain consequences for CH ₄ emissions
Savannah and pasture fires	Fire suppression	CO ₂ sequestration	Risk of catastrophic fires, change of landscape, potential loss of biodiversity
Tropical forest fires	Reduction in deforestation rates or reduced use of fire for deforestation	Biodiversity conservation, reduced CO ₂ , CH ₄ and black carbon emissions, improved air quality	
Temperate forest fires	Prescribed burning	Reduced wildfire severity and impacts	More frequent exposure to lower air quality
Tropical peat fires	Restoration of peatlands (rewetting)	Biodiversity conservation, reduced CO ₂ emissions by preventing oxidation, improved air quality	
Agricultural waste burning	Replace burning by mechanical removing of biomass and composting	Reduced CH ₄ and black carbon emissions, improved air quality	Costly, more labour intensive, potentially higher soil N ₂ O emissions
Household fires	Improve stove efficiency or replace wood stoves with stoves fired by liquefied petroleum gas	Improved (indoor) air quality, reduced landscape degradation, mitigate black carbon emissions, less time needed to collect fuelwood	

barriers and drawbacks to their implementation that need to be addressed. While the most obvious is cost, other examples are given in Table 6.2. For instance, replacing agricultural waste burning with composting could be more labour intensive and lead to higher emissions of N₂O from soils. These factors need to be carefully considered when evaluating options for reducing N₂O emissions.

6.4 Successful examples of emission reductions

Three successful examples of reducing N₂O emissions from biomass burning are described here:

1) Lowering of deforestation rates and fire emissions in the Brazilian Amazon:

According to INPE (Brazilian National Institute for Space Research)⁷⁸, deforestation rates in the Brazilian Amazon have been greatly reduced from 27,800 km²/yr in 2004 to 4,660 km²/yr in 2012. This was at least partly due to government involvement (Nepstad et al., 2009). Because fire is often used to remove biomass in the deforestation process, fire activity has decreased in parallel to the reduction of deforestation rates, except for drought years such as 2007 and 2010 when increased burning in the *cerrados* or previously cleared forests cancelled out the lower emission trends from deforestation fires. Comparing fire-related N₂O emissions in the GFED for the periods 2009-2011 versus 1997-2011 (in grid cells that according to INPE were subject to deforestation) indicates an N₂O emission reduction of about 50%.

2) Adjusting fire seasonality in northern Australia:

Several projects in the Australian savannah have

focused on abating CH₄ and N₂O emissions by introducing early season prescribed burning as described in Section 6.3.1. The largest is the Western Arnhem Land Fire Abatement (WALFA) project. Implemented over 28,000 km², the mean annual N₂O emission reduction was estimated at 37% (Russell-Smith et al, 2013) compared to the pre-project 10-year baseline.

3) Replacement of traditional stoves with Patsari cookstoves:

In several regions in Central America, the replacement of traditional stoves with so-called “Patsari” cookstoves has achieved fuelwood savings of between 44 and 67% with even larger decreases in indoor pollution levels (e.g., Masera et al., 2007; Berrueta et al., 2008; García-Frapolli, et al., 2010). These solid household stoves are designed to burn fuel more efficiently and lower heat losses. Likewise, modern prototypes, such as stoves equipped with fans or semi-gasifying stoves, can greatly reduce particulate matter and carbon monoxide emissions. Although not yet widely tested, improved cookstoves have been shown to lead to a reduction in the emissions of greenhouse gases including N₂O and methane (Bhattacharya and Abdulsalam, 2002). This reduction is expected to be proportional to the reduction in fuel wood usage.

6.5 Potential emission reductions

For 2050, it is assumed that the N₂O emission reductions already achieved in some regions, as described in Section 6.4, can be scaled up. Specifically, it is assumed that the 50% emission reductions achieved in the Brazilian Amazon (through lowering of deforestation rates and fire emissions) can be applied to all emissions (Table 6.1) from tropical forest and peat fires. This gives a reduction potential of 0.06

⁷⁸ See <http://www.obt.inpe.br/prodes>, which provides information on the satellite monitoring of the Brazilian Amazon Rainforest.

Tg N₂O-N/yr from these two sectors in 2050. In the same way it is assumed that the 37% reduction already achieved in some Australian savannahs (through the adjustment of fire seasonality) can be applied to all emissions from savannah fires. A 50% emission reduction is assumed for household stoves. No reduction is assumed for emissions from temperate and boreal forests, or agricultural waste burning. Adding up these assumptions leads to a total emission reduction potential in 2050 of 0.26 Tg N₂O-N/yr relative to baseline emissions.

It is assumed that reductions linearly increase from zero to 0.26 between 2014 and 2050, such that the potential reduction in 2020 is 0.04 Tg N₂O-N/yr.

6.6. Unresolved questions

As has been noted, estimates of fire-related N₂O emissions and the factors influencing these emissions are very uncertain and difficult to quantify. Research is needed to reduce this uncertainty. Atmospheric inversion studies have given some confidence in CO₂ emissions estimates, which are derived in the same way as N₂O emissions, but have also indicated disagreements with inventories.

One priority area for research is to understand the degree to which increased methane emission rates early in the season may offset part of the benefits of reduced N₂O emissions accomplished through early season burning. This may be the case in Africa (Korontzi et al., 2003) but not in

Australia, and may be related to the time required to cure the fuel (Meyer et al., 2012). More research is needed to resolve these differences and provide more robust calculations of the full potential for greenhouse gas savings.

6.7 Conclusions

- Biomass burning in landscape fires and household stoves currently emits a total of about 0.7 Tg N₂O-N/yr to the atmosphere. Future emissions may be similar to current rates although warming of high-latitude regions may lead to more frequent fires there.
- Options for reducing N₂O emissions from biomass burning in landscapes include reducing the use of fires for land management in forests and tropical peatlands and modification of fire frequency and fire seasonality. Options for reducing emissions from household cookstoves include improving their efficiency and using alternative fuels such as liquefied petroleum gas.
- Mitigating fires influenced by humans, such as forest clearing by fire, agricultural residue burning, and stove combustion, can bring important co-benefits such as better air quality.
- A combination of available mitigation options, if implemented, could reduce N₂O emissions from biomass burning by 0.04 and 0.26 Tg N₂O-N/yr relative to baseline emissions in 2020 and 2050, respectively.

Chapter 7

Reducing N₂O Emissions from Wastewater and Aquaculture

Lead Authors: Lex Bouwman (PBL Netherlands Environmental Agency / Utrecht University, Netherlands); Sietske van der Sluis (PBL Netherlands Environmental Agency, Netherlands)

Contributing Authors: Gui-Ling Zhang (Ocean University of China, P.R. of China); Sirintornthep Towprayoon (King Mongkut's University of Technology, Thailand); Sandor Mulsow (Universidad Austral de Chile, Chile)

7.1 Introduction

This chapter focuses on the important sources of N₂O emissions from household and industrial wastewater and from fish production through aquaculture. The chapter begins by discussing the wastewater processes leading to N₂O emissions, and then estimates the current level of these emissions, options for abating them, and the emission reduction potential. The same information is then presented for aquaculture.

Wastewater⁷⁹ can lead to N₂O emissions in two main ways. First, from the chemical and biological transformations of wastewater that take place during its treatment. Second, when wastewater is discharged to surface waters and the nitrogen contained in it is transformed by biological and chemical processes.

Aquaculture is a source of N₂O emissions because it involves cultivating freshwater and saltwater species by providing large amounts of nitrogen-rich dietary inputs (including feed, fertilizer or manure) which in turn generate substantial amounts of nitrogen rich wastes (Crab et al., 2007; William and Crutzen, 2010). The decomposition of this waste leads to N₂O emissions.

Together, wastewater and aquaculture account for approximately 4% of total gross anthropogenic N₂O emissions (Chapter 3) and their contributions are set to increase under business-as-usual conditions due to various factors discussed later.

7.2. Wastewater

7.2.1. Nitrogen flows

Nitrous oxide emissions are roughly proportional to the size of the flow of nitrogen through society and the natural environment. Therefore, to estimate nitrous oxide emissions

it is useful to start by estimating the total size of nitrogen flows.

Table 7.1 provides an overview of global nitrogen flows in the wastewater sector for year 2010 and for years 2020 and 2050 based on business-as-usual assumptions. Total nitrogen contained in household and industrial wastewater amounted to 37.6 Tg N/yr in 2010. This is not as large, for example, as world fertilizer use (107 Tg N/yr in 2010; FAO, 2010), but it is still significant. About 27% or 10 Tg N/yr of this wastewater receive some degree of treatment (Van Drecht et al., 2003; and Morée et al., 2013).

Estimates pertaining to rural regions in developing countries are particularly uncertain because of the lack of sanitation data from this part of the world. These flows are expected to increase under business-as-usual assumptions, as noted in the table, because of continued population and economic growth, and technological developments.

7.2.2. N₂O emissions associated with wastewater and wastewater treatment

Nitrous oxide is emitted from wastewater, its treatment and natural waters as an intermediate product of the biological or chemical transformation of different forms of nitrogen through “nitrification” and “denitrification”⁸⁰ (Ahn et al., 2010; Law et al., 2012; Thomson et al., 2012). Different amounts of nitrous oxide are produced by these transformations at different stages of the nitrogen flow. These different amounts are expressed here as “emission factors” which give the percentage of N₂O emissions produced per nitrogen flow. Emissions of N₂O are then estimated by multiplying these emission factors by the nitrogen flows in Table 7.1.

⁷⁹ “Wastewater” here refers to any residual water from households or industries that has been degraded in quality.

⁸⁰ Nitrification is the process by which ammonium is converted to nitrite and then nitrate. Denitrification is the process by which nitrate is converted to molecular nitrogen gas. Nitrification normally occurs in the presence of oxygen while denitrification occurs without oxygen.

Table 7.1. Global N flows in Tg of N/yr in wastewater for 2010 and for a business-as-usual scenario for 2020 and 2050.

Nitrogen flow	Assumptions	N flow (Tg N/yr)		
		2010	2020	2050
A. Total anthropogenic nitrogen in wastewater^a	Rural and urban nitrogen release (including industrial effluent)	37.6	43.6	63.9
B. Nitrogen in sewage treatment systems: Influent (B) = Removal (b1) + Effluent (b2)	Nitrogen release from inhabitants and industries with a connection to sewage system and to wastewater treatment plants.			
Primary treatment only	Mechanical	4.5	5.6	6.6
Secondary treatment only	Biological	3.5	4.9	9.5
Tertiary treatment	Advanced (aerated, anaerobic)	2.2	3.0	9.0
(b1) Nitrogen removed during treatment	Influent multiplied by removal efficiency	3.4	4.7	11.2
Primary treatment only	10% Nitrogen removal	0.5	0.6	0.7
Secondary treatment only	35% Nitrogen removal	1.2	1.7	3.3
Tertiary treatment	80% Nitrogen removal	1.8	2.4	7.2
(b2) Effluent after treatment	Total influent minus total removal	6.8	8.8	13.9
C. Leakage from sewer to groundwater	Nitrogen loss by leaks in sewage pipes are assumed to be 10%	3.5	4.0	5.6
D. Discharge from non-sewered urban population	Anthropogenic nitrogen release from urban inhabitants not connected to sewage systems, excluding ammonia volatilization and denitrification (together 20%)	3.2	3.4	3.3
E. Recycling, gaseous loss	Recycling of human waste (approximately 0.6 Tg N or 4% of urban nitrogen flows in 2010) is based on country-specific estimates; gaseous loss is 20% of urban nitrogen flow from non-connected inhabitants (see above discharge from non-sewered urban population)	5.1	5.8	7.8
F. Human excretion in rural areas	Nitrogen release from rural inhabitants; the fate is uncertain (primitive tanks, open drainage systems, defecation in surface water, latrines, septic systems, etc.)	15.6	17.0	22.1

^a The total anthropogenic nitrogen release from wastewater sector = A = B + C + D + E + F.

Table based on Van Drecht et al. (2003) and Morée et al. (2013). Estimates based on country-specific data from various sources on urban and rural population, improved sanitation and connection to sewage systems, and the presence of different treatment systems (primary, secondary, tertiary or advanced). Future estimates of household and industry emissions are based on the Global Orchestration scenario for population growth and per capita income growth (Alcamo et al., 2006). In this scenario, the gap between full access to improved sanitation and the situation in the year 2000 is assumed to be reduced by 50% in 2030, and by another 50% in 2050; the fraction of the population with a connection to a sewage system will increase likewise up until 2030, and is constant up until 2050. The nitrogen removal in wastewater treatment plants is assumed to improve by a shift of 50% of each treatment class to the next treatment class in line in the period up until 2030, and by another 50% in the period 2030-2050. More details can be found in Van Drecht et al. (2003).

N₂O emissions are produced by wastewater after it is discharged into surface waters either inland, along the coast or in the open ocean. The different forms of nitrogen in wastewater (either treated or untreated) are transformed by nitrification or denitrification in the surface waters. The emission factor in this case is assumed to be 0.5%⁸¹ of the total nitrogen content of the wastewater discharged into the natural waters (with an uncertainty range of 0.05 to 2.5%).

Nitrogen in wastewater is also transformed during the wastewater treatment process, releasing N₂O as a by-product. Here we assume an emission factor of 0.043% (with an uncertainty range of 0.035 to 0.05%) for primary and secondary wastewater treatment based on Law et al. (2012). In other words, we assume that 0.043% of the nitrogen in wastewater flowing into primary and secondary treatment plants is released to the atmosphere during treatment as N₂O.

For tertiary treatment, an emission factor of 0.6% (with an uncertainty range of 0 to 2%) is assumed, which is an average of several studies (e.g. Tallec et al., 2006; Kampschreur et al.,

2009; Ahn et al., 2010). Based on this assumption, current tertiary treatment may lead to higher emissions than direct discharge to surface water. However, generally the reduction of eutrophication by nutrient discharge is the aim of tertiary treatment in wastewater treatment.

As indicated, these numbers have wide uncertainty ranges because of the variation in treatment plant design and operation as well as other factors.

Applying these emission factors to the global wastewater nitrogen flows in Table 7.1 produces global emission estimates of 0.16 Tg of N₂O-N/yr (range: 0.02-0.77) from wastewater for 2010; 0.19 Tg of N₂O-N/yr (range: 0.02-0.89) in 2020 and 0.29 Tg of N₂O-N/yr (range 0.03-1.31) in 2050 (Figure 7.1). These are business-as-usual estimates. Emissions increase up to 2050 because of the increases in nitrogen flows in different sectors noted in Table 7.1.

7.2.3. Technical options to reduce N₂O from wastewater

The main strategy for reducing N₂O emissions from wastewater is to reduce the nitrogen content of wastewater

⁸¹ This is a rough default value from IPCC (2006). This means that about 0.5% of sewage nitrogen escapes to the atmosphere in the form of N₂O gas.

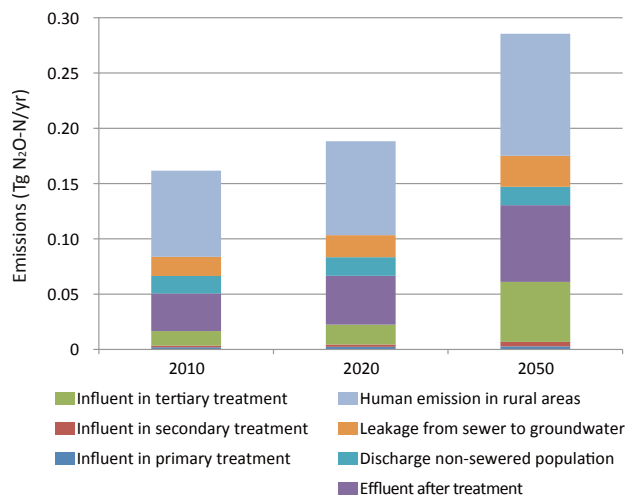


Figure 7.1: Estimated global N₂O emission from wastewater in Tg N₂O-N/yr. Based on Morée et al. (2013) and assumptions discussed in Section 7.2.2.

flows and thereby avoid emissions from taking place after wastewater is dumped into surface waters. The lower the nitrogen content of discharged wastewater, the lower the emissions of N₂O from wastewater once it is discharged into surface waters.

The first obvious option to lower the nitrogen content of discharged wastewater is to treat wastewater. As indicated in Table 7.1, the higher the level of treatment, the greater the nitrogen removal, with tertiary treatment achieving roughly 80% nitrogen removal.

Another option is to boost the efficiency of nitrogen removal of current wastewater treatment plants (Tansel et al., 2006; Law et al., 2012). One way to do this is to reduce the wastewater leaked from sewage piping. Leakage of wastewater sometimes leads to ammonia contamination of groundwater and this is a source of N₂O emissions (e.g. Wakida and Lerner, 2005). Another way is to increase the efficiency of nitrogen removal in the treatment plant (Law et al., 2012) through technical means.⁸²

Still another option is to recycle wastewater by applying it as a fertilizer on cropland (Langergraber and Muelleggera, 2005). This avoids the emissions of N₂O coming from wastewater discharged to surface waters. Applying wastewater to cultivated soils can be an economically viable alternative to synthetic fertilizers if done safely.

7.2.4. Policies and barriers to their adoption

An important example of a policy instrument leading to N₂O emission reductions is the European Union “Urban Waste Water Treatment Directive” (EEC, 1991). The aim of the Directive is to reduce nitrogen in its waste streams up to 75% and this will have many benefits, including a reduction in the amount of N₂O released to the atmosphere by wastewater.

⁸² The efficiency of nitrogen removal in an existing wastewater treatment plant can be enhanced by several means: ensuring sufficient oxygen supply during the nitrification phase of treatment, allowing for a sufficiently long sewage solids retention time, employing stepwise feeding, and ensuring adequate carbon supply during the denitrification phase of treatment (Barton and Atwater, 2002; Kampschreur et al., 2009; Yang et al., 2009; Ahn et al., 2010).

Another relevant European policy instrument is the Sewage Sludge Directive (EEC, 1986), which encourages and regulates the use of sewage sludge in agriculture. The Directive, apart from preventing harmful effects of sewage sludge on soil, vegetation, animals and humans, also helps avoid emissions that are produced by recycled sludge if it is discharged directly to surface waters or allowed to decompose.

However, implementing emission reduction strategies is not without barriers. For example, high construction and operational costs are one factor slowing down the construction of sewage systems and wastewater treatment plants, and replacement of leaky old sewage collection systems.

A barrier to the recycling of sewage sludge or wastewater as fertilizer on cropland is the possible health risk posed by the presence of heavy metals, trace organic compounds, and pathogenic organisms in the sludge or wastewater. However, this public health risk can be minimized through technical measures, which have been encouraged, for example, by the Sewage Sludge Directive mentioned above⁸³.

Another barrier to the recycling of wastewater as fertilizer is that conventional flush toilets dilute the concentration of nitrogen and phosphorus in sewage, making it unsuitable for use as fertilizer. Since wastewater recycling requires a substantial capital investment, a long-term perspective is needed for gradually implementing this approach for achieving multiple benefits of water conservation, cost savings for fertilizer, and emission reductions (Langergraber and Muelleggera, 2005).

7.2.5. Emission reduction potential

Emissions of N₂O are likely to increase under business-as-usual conditions of increased population and economic growth (Figure 7.1). This is despite the assumption of much wider coverage of advanced wastewater treatment (Table 7.1). Here we estimate the potential to reduce emissions relative to these business-as-usual estimates.

First, a 95% emission reduction is assumed through improved management in the wastewater treatment sector, based on Kampschreur et al. (2009) who show that zero N₂O emissions are possible in tertiary treatment plants. This will lead to a decrease in the emission factor of tertiary treatment plants and would result in a reduction of 0.02 Tg N₂O-N and 0.05 Tg in 2020 and 2050, respectively.

Second, it is assumed that all primary and secondary wastewater treatment plants under business-as-usual conditions are upgraded with tertiary treatment facilities in 2020, and that the 95% emission reduction for tertiary treatment as described above is achieved. This would reduce N₂O emissions by 0.03 Tg N₂O-N/yr in 2020 and 0.04 Tg N₂O-N/yr in 2050 relative to the baseline in these years, because of the reduced load of nitrogen to surface waters.

Third, a 100% reduction of leakage from sewage systems is assumed, and treatment of this amount in well-managed treatment plants with 95% emission reduction compared to the current situation. This will lead to an emission reduction

⁸³ However, it was also noted that only a few Member States have very high sludge reuse rates. For more details, please see: http://europa.eu/legislation_summaries/agriculture/environment/128088_en.htm

of 0.001 Tg N₂O-N/yr in 2020 and 0.0014 Tg N₂O-N/yr in 2050.

Finally, a major boost in the recycling of wastewater and sludge as fertilizer on agricultural land is assumed. If 50% of the waste from urban populations lacking sewage connection is collected and recycled, a reduction of 0.01 Tg N₂O-N/yr will be achieved in both 2020 and 2050⁸⁴. If, in addition, 25% of waste from rural populations is collected and recycled, this would lead to a reduction of 0.02 Tg N₂O-N/yr in 2020 and 0.03 Tg N₂O-N/yr in 2050 compared to the baseline.

Adding up these options, gives an N₂O emission reduction potential from wastewater of 0.08 Tg N₂O-N/yr below the baseline in 2020, and 0.13 Tg N₂O-N/yr in 2050.

7.2.6. Unresolved questions

A major source of nitrogen to coastal seas is wastewater, and this contributes to eutrophic conditions in these seas (Seitzinger et al., 2010). If eutrophic conditions are severe they could lead to low-oxygen conditions and in some cases to the temporary depletion of oxygen (Diaz and Rosenberg, 2008; Zhang et al., 2010). In this situation, these seas could be a significant source of N₂O (Naqvi et al., 2010; Freing et al., 2012; Zamora et al., 2012). Since these low-oxygen zones may be increasing, they could also lead to an increase in N₂O emissions. This example presents yet another benefit of expanding wastewater treatment, but also the need for further research about coastal eutrophication.

7.3. Aquaculture

7.3.1. Nitrogen flows

Similar to emissions from wastewater, we estimate the release of N₂O from aquaculture by first estimating flows of nitrogen and then multiplying them by emission factors. Total aquaculture production results in the release of about 4.6 Tg N/yr in 2010, computed by subtracting nitrogen in feed input minus harvested fish (Table 7.2). The percentage of nitrogen in harvested fish relative to feed input was only 20% in 2010, which is the mean for all fish species and production systems in inland and marine waters (Bouwman et al., 2011; Bouwman et al., 2013). Nitrogen flows are expected to increase in the future under a business-as-usual scenario (see Table 7.2).

7.3.2. N₂O emissions associated with aquaculture

Here we estimate emission factors for N₂O which have the same form as those for wastewater, namely, the percentage of N₂O emissions produced per nitrogen flow. Emissions of N₂O are then estimated by multiplying these emission factors by the nitrogen flows in Table 7.2. Here, we use an emission factor of 1% of the nitrogen input as a best estimate which is close to the value of 1.3% from Hu et al. (2013). The uncertainty range is from 0.5% (IPCC, 2006) to 5% (Williams and Crutzen, 2010). The emission factors used here are higher than those for wastewater due to the fact that a large fraction of aquaculture is in ponds or other confined systems (Bouwman et al., 2011; Bouwman et al., 2013), where conditions may be more prone to N₂O emissions than

Table 7.2. Global N flows in Tg per year in global freshwater and marine culture of shellfish and finfish aquaculture for 2010, and a business-as-usual scenario for 2020 and 2050.

	N flow (Tg N/yr)		
	2010	2020	2050
Feed intake	5.7	7.9	10.6
Fish harvest	1.2	1.7	2.5
Waste	4.6	6.2	8.1

Based on (Bouwman et al., 2011; Bouwman et al., 2013). For 2010, most global production was in Asia (97% for finfish and 93% for shellfish), with over half in East Asia. Finfish represented 83% of total feed nitrogen intake (of which 88% was freshwater), while shellfish contributed 17% (of which two thirds was marine). Future estimates of emissions are based on the Global Orchestration scenario for population growth and per capita income growth (Alcamo et al., 2006). Annual growth rates calculated from Delgado et al. (2003) and IFPRI (2003), which provide an estimate of future aquaculture production in high-value and low-value finfish whereby the growth rate for a specific species is assumed to be the same for inland and marine production. Further scenario assumptions were made for the feed conversion ratio (FCR), apparent digestibility of feed, nutrient content of the feed, and the fraction of compound feed. See (Bouwman et al., 2011; Bouwman et al., 2013) for more details.

open surface waters. Applying these emission factors to the waste in the nitrogen flows of Table 7.2 provides baseline estimates of N₂O emissions from aquaculture of 0.05 (0.02-0.23) Tg N₂O-N/yr in 2010; 0.06 (0.03-0.31) Tg N₂O-N/yr in 2020, and 0.08 (0.04-0.41) Tg N₂O-N/yr in 2050.

7.3.3. Technical options to reduce N₂O from aquaculture

One option available in Asia and elsewhere to reduce total N₂O emissions from agriculture and aquaculture is to combine them into “integrated agriculture-aquaculture farming systems” (e.g. Tacon and De Silva, 1997; Michielsens et al., 2002; Ahmed et al., 2007). In such systems, farmers add manure to ponds to increase plant and fish productivity. The type, quality and dose of manure or fertilizer used to fertilize ponds for increasing plankton production and fish growth are important determinants of a pond’s environmental impacts (Michielsens et al., 2002; Kumar et al., 2004; Matthews et al., 2004). Conversely, solid wastes and nutrient-rich water from ponds can be used as manure for cropping, and aquatic plants can be used as animal feed (Sindilariu, 2007). With proper fertilizer and manure management, integration of agriculture and aquaculture can lead to higher total nitrogen use efficiency (with an associated reduction in N₂O emissions) at the farm level compared to separate crop, livestock and fish production systems. Data on N₂O emissions from such integrated systems are required to verify this expectation.

Another promising strategy is to reduce nitrogen waste by combining different trophic levels of aquatic species (salmon, shellfish, algae) in an “integrated aquaculture system” where the waste from one species is the food for another (Neori et al., 2004; Ridler et al., 2007; Abreu et al., 2009; Barrington et al., 2009; Soto, 2009; Troell, 2009). This could be a promising option although it is not yet widely practiced because of difficulties in combining the management of different species and production systems in one farm. The potential savings in nitrogen inputs, and associated N₂O and other emissions could be very large. For example, a system including finfish and seaweed can effectively remove as much as 60% of the nitrogen produced by a sea bass farm (Hernández et al.,

⁸⁴ Assuming that the urban population lacking a sewage connection is more or less constant between 2020 and 2050. See table 7.1

2002), and a substantial part of the nitrogen produced by a salmon farm (Abreu et al., 2009).

Another option is a “polyculture-based aquaculture farming system” which consists of a pond stocked with a carefully selected population of fish species having different non-competitive, complementary feeding habits (Tacon, 1998). Polyculture can increase the efficiency of feed use and nutrient retention compared to monoculture (Tacon, 1998). Preliminary results (Gui-Ling Zhang, personal communication) indicate that it may reduce N₂O emissions from intensive aquaculture systems. Further research is needed, however, to assess the effectiveness of this option.

An effective approach has been to modify feed and nutrient inputs to aquaculture ponds in order to improve their digestibility and efficiency of utilization, and this in turn reduces waste output from fish farming. Bureau and Hua (2010) reported a reduction of approximately 15% in total nitrogen wastes (solid and dissolved) from the production of rainbow trout through better selection and processing of ingredients, improved feed formulation and the use of various feed additives, such as enzymes. (NRC, 2011). Using this approach, wastes can also be reduced in the farming of carp, catfish and tilapia (Bureau and Hua, 2010).

Another option is to use aeration to limit or avoid denitrification and consequent N₂O production in pond systems (Chandran et al., 2011). Finally, nutrient outflow from pond systems can be reduced through effluent treatment. For example, screening and sedimentation can remove nitrogen-rich suspended solids before they are discharged to surface waters (Bergheim and Brinker, 2003).

7.3.4. Barriers

A large fraction of current aquaculture employs semi-intensive and extensive production systems with low nitrogen use efficiencies. Hence, implementing some of the strategies described above, together with training and education of farmers, can be a slow process. Public policies should also be investigated for encouraging increases in production efficiency. This, in turn, would help reduce N₂O emissions from aquaculture facilities.

In current aquaculture, integrated production systems are not widespread, possibly due to the difficulty in managing and culturing multiple species in rapidly intensifying production systems. Further research is therefore needed on these systems.

7.3.5. Emission reduction potential

Over the coming years it is likely that aquaculture production will increase because of increasing population, a greater accent on fish consumption, and a continuing market shift to fish farming. Along with this growth will come an increase in nitrogen flows (Table 7.2) and accompanying N₂O emissions (Section 7.3.2). On the other hand, we articulated above some of the many options for drawing down N₂O emissions from the baseline.

All of the above options work towards improving the *nitrogen use efficiency* of fish production which leads to a reduction in nitrogen inputs and discharges, and thereby to reduced N₂O emissions. While the aggregate nitrogen use efficiency is now around 40% in salmonid aquaculture (Bouwman et al., 2013), it may be 20-30% in most other mariculture and freshwater aquaculture depending on the species cultured (Bouwman et al., 2011; Bouwman et al., 2013). Based on the options described in Section 7.2.3 and Bureau and Hua (2010) it may be feasible to increase this efficiency to 40% in most feed-dependent aquaculture systems by 2020. This would reduce nitrogen waste by around 20% and consequently N₂O emissions by the same percentage. This will be equivalent to an emissions reduction potential of approximately 0.01 and 0.02 Tg N₂O-N/yr below the baselines in 2020 and 2050 respectively. Hence, emissions in 2020 and 2050 after mitigation could be approximately 0.05 Tg N₂O-N/yr and 0.06 Tg N₂O-N/yr respectively.

7.3.6. Unresolved questions

Similar to other waste-related emissions of N₂O, emissions from aquaculture waste are not well understood. Denitrification in fish ponds may be considerable (Gross et al., 2000), but little is known about the processes of N₂O production in the ponds. Similarly, we also know little about emissions from cage aquaculture in marine ecosystems. Further measurements would be needed to reduce uncertainties.

7.4. Conclusions

- Wastewater and aquaculture account for approximately 4% of total anthropogenic N₂O emissions. It can be expected that these emissions will increase in magnitude under business-as-usual assumptions due to population growth and anticipated trends in consumption patterns.
- Reduction of nitrogen flows in wastewater and aquaculture is an important strategy for preventing N₂O formation. This can be accomplished by increased recycling of nitrogen flows and by improving the efficiency of fish production.
- Technical options for minimizing N₂O emissions in wastewater treatment and recycling nitrogen waste could add up to an emission reduction potential of 0.08 Tg N₂O-N/yr by 2020, and 0.13 Tg N₂O-N/yr by 2050, resulting in a total emission reductions of approximately 45% by 2050.
- Increasing the aggregate nitrogen use efficiency in the aquaculture sector would reduce N₂O emissions by about 20% below their baseline values, leading to an emission reduction potential of approximately 0.01 and 0.02 Tg N₂O-N/yr below the baselines in 2020 and 2050 respectively.

Chapter 8

Drawing-Down N₂O Emissions: Scenarios, Policies and the Green Economy

Lead Authors: Mark A. Sutton (NERC Centre for Ecology and Hydrology, UK), Ute M. Skiba (NERC Centre for Ecology and Hydrology, UK), Eric Davidson (Woods Hole Research Center, USA), David Kanter (Princeton University, USA)

Contributing Authors: Hans J. M. van Grinsven (PBL Netherlands Environmental Assessment Agency, The Netherlands), Oene Oenema (Wageningen University, The Netherlands), Rob Maas (RIVM, National Institute for Public Health and the Environment, The Netherlands), Himanshu Pathak (Indian Agricultural Research Institute, New Delhi, India).

8.1. The N₂O challenge

Previous chapters have presented a wide range of options to reduce anthropogenic N₂O emissions. It remains to ask whether these options are already being adopted, and if not, then what would be needed to encourage and enable them.

This chapter argues that there is substantial benefit to be found from reducing N₂O emissions, especially when actions to tackle N₂O help improve the efficient use of nitrogen compounds, simultaneously avoiding other nitrogen pollution problems. From this perspective a stronger emphasis on N₂O reduction can contribute multiple benefits for businesses and the environment and can be linked to the larger goals of the “green economy.”

In the following, we draw on the preceding chapters to summarize the global potential for N₂O emission reductions, and how it would reduce emissions in terms of global warming potential and ozone depletion potential. We then examine how N₂O mitigation can fit into ideas of the green economy and help turn the potential into actual emission savings. We end by reflecting on international structures that can support action.

8.2. Scenarios for reducing N₂O emissions

As described in Chapter 3, projections depend on many different driving forces including: changes in human population; per capita consumption of food, especially meat; food wastage; and nutrient use efficiency in crop and livestock production. Each of these factors is linked to the production of new usable forms of nitrogen for food, fibre and bioenergy production. Other driving forces include technological improvements in industry, energy, and transportation sectors; air pollution (which leads to N deposition onto soils and aquatic systems); the frequency of prescribed and wild fires; land-use change; and climate.

Several published scenarios based on these and other driving forces were reviewed in Chapter 3, along with a synthesis of inventories of current emissions. The potentials for mitigation of N₂O emissions in agriculture, industry, biomass burning, sewage treatment, and aquaculture were reviewed in Chapters 4-7. Here we derive a new set of scenarios based on this report’s best estimates of current emissions and future mitigation potential. We compute a business-as-usual scenario (BAU) and four mitigation scenarios to make up a set of five cases referred to as cases from “This Report” (TR):

TR Case 1. Business-As-Usual. In this scenario, the driving forces of emissions are assumed to increase according to the assumptions presented in Chapters 4 to 7.

TR Case 2. Mitigation of Industry, Fossil Fuel Combustion and Biomass Burning. This scenario assumes that the combined emissions from industry, fossil fuel combustion and biomass burning are reduced by 28% in 2020 relative to BAU and 58% in 2050, as described in Chapter 5.

TR Case 3. Efficiency of Agricultural Production. This scenario assumes decreases in fertilizer use, manure production, and emission factors relative to BAU, associated with an increase in the nitrogen use efficiency of agricultural production, as described in Chapter 4 (incorporating Options 1 and 2 of Table 4.4).⁸⁵

⁸⁵ The method of Davidson (2009) was used to derive new emission factors (EFs) for N₂O emissions associated with use of N fertilizers and the production of manure, including direct on-farm emissions and all downwind and downstream emissions. In brief, the “top down” modeling described in Chapter 3 was used to estimate total anthropogenic N₂O emissions, and then the best estimates of emissions from industry, transportation, energy, biomass burning, and land-use change were subtracted, leaving the remainder as emissions attributable to agriculture. Current estimates from this report and historical estimates (Davidson, 2009; Lamarque et al., 2010) were used in a regression analysis to estimate the EFs of annual fertilizer-N use and manure-N production from 1860 to 2005. The new EFs are 2.37% and 1.71% for fertilizer and manure, respectively. These values are somewhat lower than those reported by Davidson (2009), because that study used somewhat lower estimates of non-agricultural emissions.

Table 8.1. Projections of net anthropogenic N₂O emissions (Tg N₂O-N/yr) based on this report’s assessment of current emissions and potential mitigation scenarios by sector.

	2005	2020	2030	2040	2050
TR Case 1. Business-as-Usual	5.3	6.7	7.6	8.2	8.9
TR Case 2. Mitigation of industry, fossil fuel combustion and biomass burning	5.3	6.2	6.7	7.1	7.6
TR Case 3. Efficiency of agricultural production	5.3	6.2	6.2	6.1	5.8
TR Case 4. Efficiency of agricultural production and consumption (food changes)	5.3	5.7	5.3	4.9	4.5
TR Case 5. All Mitigation actions	5.3	5.2	4.4	3.8	3.1

TR Case 4. Efficiency of Agricultural Production and Consumption. This scenario includes efficiency improvements on the production side of agriculture from TR Case 3, plus additional efficiency improvements on the consumption side as a result of reductions in food waste and lower per capita consumption of meat in the developed world. These changes in consumption lead to a further lowering of demand for fertilizer nitrogen and the production of manure, as described in Chapter 4 (incorporating Options 3 and 4 of Table 4.4).

TR Case 5. Combined Mitigation. This scenario combines all the mitigation options of TR Cases 2-4.

Projected emissions for each of these scenarios are presented in Table 8.1. According to BAU, emissions of N₂O for 2050 are 68% higher than in 2005. Hence, failing to take action in mitigating N₂O will lead to substantial increases in its emissions over the coming decades. Nevertheless, this is a smaller increase than other published BAU scenarios (see Chapter 3 and Figure 8.1) because we assume that BAU will include some on-going improvements in agricultural efficiencies (Chapter 4).

The scenarios “Mitigation of Industry and Biomass Burning” and “Efficiency of Agricultural Production” lead to smaller increases by 2050, with N₂O emissions being 43% and 9% higher than in 2005, respectively. Hence taking action in these sectors alone can only slow down the upward trend in emissions.

The scenario that combines efficiency improvements in agricultural production and consumption (TR Case 4) projects a 15% decrease of emissions in 2050 relative to 2005, showing the substantial additional effect of reducing food losses and changing diets.

Finally, the “Combined Mitigation” scenario projects a decrease in N₂O emissions of 42% by 2050 as compared with 2005. This emphasizes how concerted action across all sectors can make a substantial contribution to reducing global N₂O emissions. Note that the concerted mitigation scenario from this report is more ambitious (projections of the lowest emissions shown in Figure 8.1) than the other published scenarios we term “concerted”. As a general conclusion, the emission reduction measures identified in previous chapters can significantly slow down and even reverse the trend of increasing global N₂O emissions over the coming decades.

8.3. Relevance of reduced N₂O emissions for protecting climate and the ozone layer

The new scenarios described above provide useful information about the potential to turn around global N₂O emission trends given different mitigation actions. Here

we combine these new scenarios with the set of published N₂O emission scenarios reviewed in Chapter 3 and examine their collective message about the range of N₂O emission reduction potentials. (Note that the results presented here are not the same as in Chapter 3. Here we consider composite results of the three scenario sets from Chapter 3 together with the new scenario set summarized in Table 8.1.)

As explained in Chapter 3, all scenarios are normalized to 2005 emissions of 5.3 Tg N₂O-N (this report’s best estimate of net anthropogenic emissions) in order to enable comparisons despite differences in base years and emissions for these base years among these studies.

The scenarios are clustered into three groups⁸⁶:

Business-as-usual scenarios. These are scenarios with no or little mitigation. On average, the emissions of these scenarios increase to 9.7 Tg N₂O-N/yr by 2050, which is nearly double their level in 2005 (83% increase).

Moderate mitigation scenarios. These are scenarios in which emissions rise at a slower rate than business-as-usual. Here emissions grow on average to 6.7 Tg N₂O-N/yr by 2050, an increase of 26% relative to 2005. Hence moderate mitigation actions significantly slow down the growth of N₂O emissions.

Concerted mitigation scenarios These are scenarios in which emissions decrease between 2005 and 2050. On average, emissions decline to 4.2 Tg N₂O-N/yr by 2050, a decrease of 22% relative to 2005. These scenarios “bend the curve” of rising global N₂O emissions.

As noted in Chapter 3, the published “concerted mitigation” scenarios result in near stabilization of atmospheric concentrations of N₂O between 340 and 350 ppb by 2050, whereas N₂O concentration continues rising beyond 2050 for the BAU and moderate mitigation scenarios.

The differences between BAU and the mitigation scenarios reveal the potential to reduce global emissions of N₂O, with significant implications for N pollution, climate change and stratospheric ozone depletion (Figure 8.1).

These potentials are apparent in Table 8.2, which shows the emissions for 2020, 2030, 2040 and 2050 in terms of annual amounts of nitrogen pollution (Tg N₂O-N), carbon

⁸⁶ The following scenario sets are included: Scenarios from this report (Table 8.1); SRES (Nakicenovic et al. 2000); RCP (Van Vuuren et al. 2011a), and Davidson (2012). The last three are reviewed in Chapter 3. The scenarios are grouped into three categories.

- **Business-as-usual scenarios** (TR Case 1 from Table 8.1, RCP 8.5, SRES A2, and Davidson S1);
- **Moderate mitigation scenarios** (TR Cases 2 and 3 from Table 8.1, RCP 4.5, RCP 6.0, SRES A1, SRES B1, and Davidson S2 and S3);
- **Concerted mitigation scenarios** (TR Cases 4 and 5 from Table 8.1, RCP 2.6, SRES B2, and Davidson S4 and S5).

dioxide equivalent (Gt CO₂eq), and ozone depletion potential (ODP Kt).

By 2020 the set of concerted mitigation scenarios are about 1.8 Tg N₂O-N/yr or 25% below the BAU scenarios.⁸⁷ In terms of carbon dioxide equivalents, this is about 0.8 Gt CO₂ eq/yr less than BAU. The 0.8 Gt CO₂ eq/yr can be compared to the “emissions gap” in 2020 of 8-12 Gt CO₂ eq which needs to be closed to have a “likely” chance of meeting the global 2°C climate target (UNEP, 2013a).⁸⁸ Therefore, determined action over the coming few years on reducing N₂O emissions can help close up to 10% of the gap.

By 2050, the concerted mitigation scenarios are around 5.5 Tg N₂O-N/yr or 57% lower than BAU³, or about 2.6 Gt CO₂ eq/yr lower. Therefore, the abatement of N₂O can make an even greater contribution to the mitigation of nitrogen pollution and climate change over the medium-term.

Another way to look at the climate-related benefits of N₂O reductions is to sum up the avoided emissions between 2013 and 2050. This amounts to about 122 Tg N₂O-N, which is equivalent to about 57 Gt CO₂eq. This is nearly double the global energy-related CO₂ emissions in 2012 of 32 Gt CO₂ (IEA, 2013).

To assess their impact on ozone layer depletion, N₂O emissions can be weighted according to their ozone-depleting potential (ODP). Emissions in these terms are shown in the bottom rows of Table 8.2. On the average, the set of concerted mitigation scenarios in 2050 are ODP 147 Kt/yr below business-as-usual. This amount is equivalent to a 13% decrease in chlorofluorocarbon (CFC) emissions from their peak in the late 1980s. Because N₂O is anticipated to remain the dominant ozone depleting substance emitted for the remainder of the 21st century (Chapter 2), the concerted mitigation scenarios would roughly halve the ozone-depleting effect of anthropogenic emissions in 2050 as compared with BAU.

Another way of gauging the effectiveness of N₂O emission reductions is to estimate the magnitude of avoided emissions over the coming decades in terms of their ability to deplete the ozone layer. If the emissions avoided by the concerted mitigation scenarios are summed up between 2013 and 2050, they amount to an equivalent of 3270 Kt of CFC-11 emissions. This is of comparable magnitude to the kilotons of ozone depletion potential (ODP Kt) estimated to be locked up in the stock of old refrigerators, air conditioners, insulation foams, and other units (1550-2350 ODP Kt), otherwise referred to as banks⁸⁹. This stock is considered the most significant remaining source of ozone depleting substances for which action should be taken to accelerate ozone layer recovery (UNEP, 2010).

As discussed in Chapter 3, the expansion of biofuels could have a large influence on future N₂O emissions. This factor is

87 This refers to the mean of the four scenarios: SRES, RCP, Davidson and this report. The Case 5 scenario for this report estimates 1.5 Tg N₂O-N/yr below BAU for 2020 (Table 8.1).

88 The ‘emissions gap’ in 2020 is the difference between global emission levels in 2020 consistent with meeting the 2°C target, and levels expected in that year if country emission reduction pledges are met. The 2°C target (keeping the increase in global average temperature to less than 2°C relative to pre-industrial) was agreed upon by parties at the Conference of Parties of the Climate Convention in Cancun in 2010. See UNEP (2013) for details about the emissions gap. A “likely” chance refers to a greater than, or equal, probability of 66%.

89 Banks are stocks of ozone depleting substances that have already been manufactured and used, but not yet released to the atmosphere.

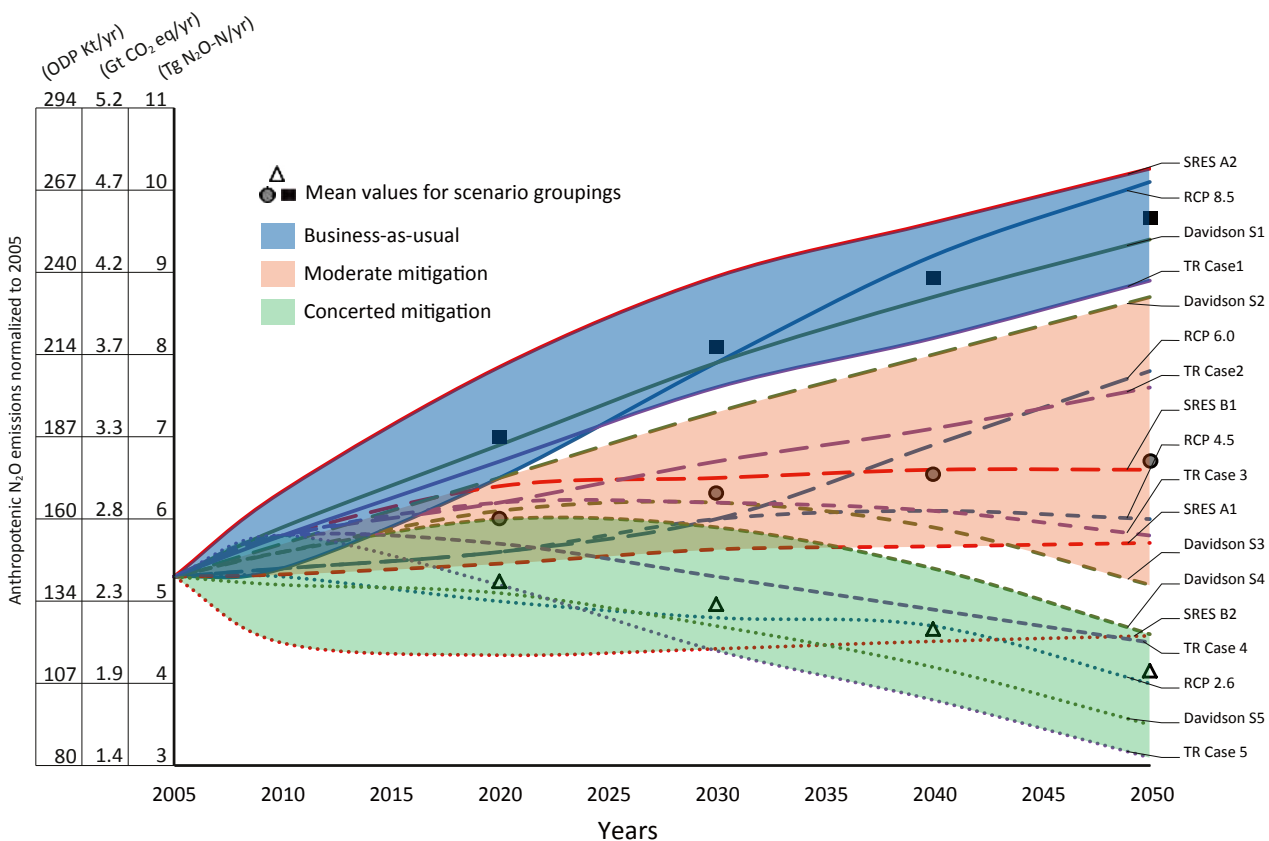


Figure 8.1: Projections of anthropogenic N₂O emissions according to the business-as-usual, moderate mitigation, and concerted mitigation scenarios, based on calculations in this report and previous calculations. The mean for each grouping of scenarios are shown by square, circle, and triangle markers, respectively.

Table 8.2. Projected annual anthropogenic N₂O emissions based on calculations of this report and previous calculations. Emissions for three scenario groupings given in units of nitrogen, CO₂ equivalents and ozone depletion potential.

	2020	2030	2040	2050
Units: Nitrogen equivalents (Tg N₂O-N/yr) *				
Business-as-usual	7.0	8.1	8.9	9.7
Moderate mitigation	6.0	6.3	6.5	6.7
Concerted mitigation	5.2	5.0	4.7	4.2
Units: Equivalents of carbon dioxide (Gt CO₂ eq/yr)**				
Business-as-usual	3.3	3.8	4.2	4.5
Moderate mitigation	2.8	3.0	3.1	3.1
Concerted mitigation	2.5	2.3	2.2	1.9
Units: Ozone depletion potential (ODP Kt/yr)***				
Business-as-usual	187	216	238	258
Moderate mitigation	160	169	175	178
Concerted mitigation	140	133	125	111

* The values given here are the mean of four sets of scenarios according to SRES, RCP, Davidson and the calculations of this report, and therefore differ from the values given in Table 8.1, which refer specifically to the calculations of this report.

** Calculated using a 100-year global warming potential of 298 for N₂O

*** Calculated using an ozone depletion potential of 0.017 for N₂O

not included in these scenarios due to the wide uncertainty about the potential land area devoted to biofuels, about future energy demand for biofuels, and about their extra fertilizer requirements. Projections for biofuels are explored in Chapter 3 (Box 3.1).

To sum up, the collection of scenarios agree that concerted action can significantly draw down N₂O emissions relative to business-as-usual, both in the near term (2020) and over the longer term (2050), contributing substantially to the protection of climate and the ozone layer. To achieve a reduction in emissions relative to 2005, rather than simply a slowing down of their rate of increase, will require substantial mitigation efforts in all the main source sectors (Table 8.1).

8.4. Realizing N₂O reduction potential through the green economy

The preceding chapters show the significant potential to reduce emissions of N₂O from many aspects of the economy – the manufacturing of chemicals, the burning of fuels in households and transportation, the treatment of wastewater, the production of fish through aquaculture, and most importantly, the cultivation of crops and rearing of livestock. With these economic connections in mind, it makes sense to think about N₂O mitigation as part of a larger effort to build a “green economy” linked to better overall N management.

There are many different views of what constitutes green economy.⁹⁰ According to the UNEP Green Economy Report, green economy is an economy that encompasses all the economic opportunities arising from actions that promote

90 Concerning contrasting views of the green economy, see Sutton et al. (2014), including an explanation of the critical distinction between the *Sector View* (green actions consistent with improved sector profit) and the *Societal View* (net economic balance, combining the Sector View with all other factors, incorporating the value of reducing pollution threats on climate, human health and ecosystems). Recognizing these different views and finding ways to bring them closer together is fundamental to overcoming the barriers-to-change to reducing N₂O emissions through the green economy. Allen and Clouth (2012) provide an overview of recent perspectives and definitions in the green economy.

sustainability, improving “human well-being and social equity, while significantly reducing environmental risks and ecological scarcities” (UNEP 2010). A related concept, ‘green growth’ is also frequently used, and focuses more on the contribution of environmental technologies to a growing economy (OECD, 2011). Green economy thinking is also centrally embedded within the Rio+20 Declaration (UN, 2012).

Whatever the emphasis, there are strong shared challenges for everyone, where actions to reduce N₂O emissions become part of a wider effort to improve green economic performance by both businesses and consumers. This can enhance human wellbeing though improved environmental quality with reduced threats to climate, human health and ecosystems, while contributing to global food and energy security.

8.4.1 Nitrogen use efficiency

A central idea for linking N₂O mitigation with green economic performance is the concept of “nitrogen use efficiency” (NUE). This concept applies across many scales, from an agricultural field (Chapter 4) to the full chain of national nitrogen flows in the economy (Box 8.1)⁹¹. At its simplest, NUE is the ratio of nitrogen contained in a product (such as grain, meat or a manufactured chemical) divided by the amount of nitrogen used to produce that product. Therefore, the higher the NUE, the lower the N losses, and this includes N₂O released to the atmosphere. The result is that measures focused on improving NUE contribute to a reduction in N₂O and other nitrogen emissions per unit of product produced. While there are both trade-offs and synergies involved in managing the N cycle, an emphasis on improving efficiency provides the key to maximizing the co-benefits. For example, good fertilizer management increases the fraction of fertilizer taken up

91 For a discussion of different definitions of NUE in crop systems, see Dobermann and (2007) and Snyder and Bruulsema (2007). Sutton et al. (2013a) define the concept of full-chain NUE, and compare first estimates with crop NUE estimates at the national scale for 121 countries of the world. Other useful indicators include regional nitrogen balances (surpluses and deficits), with the aim to use all available N resources. The use of nitrogen balances complements NUE, giving a more complete picture (UNECE, 2012).

by crops, reduces the losses of N, and thereby lowers N₂O emissions (Oenema et al., 2011).

If we consider the entire chain of nitrogen flows in the economy (Box 8.1), we can speak about “full-chain nitrogen use efficiency”, meaning the ratio of N in final products for human use divided by *all* the new nitrogen inputs needed for these products. While it is also important to address the NUE efficiency of each stage in the chain, this ‘whole-systems perspective’ helps decision makers to see the overall efficiency of human nutrient use, while offering flexibility in the options that can be used to improve performance. The options include improving technical efficiency at each stage, as well as optimizing food choices, reducing food waste and improving nitrogen recycling practices to improve overall system efficiency.

Besides reducing N₂O emissions, increasing the full-chain NUE has many benefits, including the simultaneous reduction of air pollutants such as nitrogen oxides and ammonia; and water pollutants such as nitrates (Skiba et al., 2012; Reay et al., 2012; Sutton et al., 2013a).

8.4.2. Costs and benefits in the context of the nitrogen cycle

The potential contribution of improving NUE to the green economy can be shown using calculations from the recent Global Overview on Nutrient Management.⁹² This included estimates of what would be achieved by a goal to improve NUE by 20% by the year 2020. It was calculated that such an improvement would provide a global saving of 23 million tonnes of nitrogen, worth an estimated US \$23 billion (range: \$18-\$28 billion). The value of annual benefits to the environment, climate and human health was much larger, estimated at US \$160 billion (range: \$40-\$400 billion). By comparison, the annual costs of actions to increase NUE were estimated at about US \$12 billion (range: \$5-\$35 billion). The following important conclusions can be drawn from these estimates:

- Of relevance to businesses, the estimates highlight that the value of the N saved through improved NUE can be larger than the cost of taking action. A key example is improved management and recycling of fertilizers and manures, allowing farmers to reduce fertilizer costs (Chapter 4). The ongoing challenge is to further up-scale such methods to reduce costs and risks, strengthening the business case for action. Scaling-up may initially require financial and other incentives to increase the profitability of taking action, and as a catalyst for stimulating green development.
- From society’s viewpoint, the estimates given above show that the benefits of improving NUE for the environment, climate and human health are substantially larger than the direct costs and benefits to business associated with taking action. This means that there is a very strong economic case for society to develop actions that stimulate improved NUE with reduced N₂O emissions.

92 Sutton et al. (2013a) drawing on the approach of Brink et al. (2011) and van Grinsven et al. (2013). The following calculations were based on a relative improvement in national NUE using 2008 as a reference.

- The impact of N₂O in these estimates makes up 3.5% of the total environmental costs that have been monetized, hence a very modest fraction.⁹³ This emphasizes the substantial added value to be found by linking N₂O emission reductions to increasing overall NUE performance across the nitrogen cycle.

For policymakers to accept the economic case for reducing N₂O emissions, it must be clear that the monetary value of the benefits are substantial. Yet benefits such as better public health, a clean environment and a protected climate are usually not monetized and do not show up as part of national Gross Domestic Products (GDP). In addition, the beneficiaries are often different from those absorbing additional costs. This can provide a significant barrier-to-change which may be addressed at the societal scale (Sutton et al., 2014).

It is feasible to value several of the benefits of N₂O mitigation such as improved NUE and its side benefits, as shown in the above example and other work (e.g. Birch et al., 2011; Compton et al. 2011; Gu et al., 2012). This valuation can make a good contribution to comprehensive national accounting systems for natural capital where the value of protected forests, waterways and soils can be monitored and where the value of protecting this natural capital through nitrogen mitigation can be assessed.

There is still some way to go in incorporating N₂O mitigation into the green economy. Until recently, N₂O mitigation had often taken a back seat compared with efforts to reduce CO₂ and CH₄. However, a comparative analysis by Winiwarter et al. (2010) for different greenhouse gases shows a higher share of N₂O emissions can be mitigated compared to the share of CO₂ emissions in the low cost-range (<5 €/ton CO₂-eq), suggesting that N₂O mitigation might be more cost-effective.

The benefit-to-cost ratio could also be larger for N₂O than for CO₂, as improved nitrogen management simultaneously addresses many different environmental issues while contributing to improved food security. This is evident from the large share of the estimated environmental benefits of improving NUE that are associated with human health and ecosystem benefits, which are in addition to the climate benefits⁹⁴.

8.4.3. N₂O in relation to human consumption

It is also vital to consider N₂O control within the context of future societal aspirations for sustainable consumption patterns. The central issue here is the dominating influence of livestock farming on the global agricultural system as a whole, where an estimated 82% of nitrogen in harvests (including forage) goes to feeding livestock, with less than 20% of nitrogen in harvests feeding humans directly (Sutton

93 Based on the N₂O costs associated with climate and human health (stratospheric ozone depletion) being around 3.5% of the total estimated costs of N pollution (van Grinsven et al., 2013), combined with estimated total N costs at a global scale of US \$800 billion/yr (range: \$200 - \$2000 billion) (Sutton et al., 2013a). With a global 20% improvement in NUE for a constant output scenario, the estimated climate and health benefits from reduced N₂O emissions are therefore estimated at US \$6 billion/yr (range: \$1.4-\$14 billion).

94 See previous footnote.

et al., 2013a). At the same time, affluent citizens in many countries are consuming more protein than needed. For example, in Europe the average citizen consumes 70% more protein than needed based on dietary guidelines (Reay et al., 2011).

There are several consequences of these observations. Firstly, citizens in the developed world are setting a standard for food consumption patterns, especially of meat and dairy products, that is far from being sustainable, while at the same time leading to significant additional health risks through over consumption (WHO/FAO, 2002). Secondly, many people in the developing world are aspiring to western food consumption patterns, with increasing per capita rates of meat and dairy consumption. While there is a critical need for improved diets among the world's poorest, a matching challenge is arising in some parts of the developing world where increasing consumption of meat and dairy products, combined with increasing world population, is setting the stage for a substantial worsening of N₂O and N pollution (Table 8.1; Winiwarter et al., 2013).

Reducing excess meat and dairy consumption in the developed world is expected to have several positive consequences: a) full-chain NUE would increase, b) N₂O and other N emissions would substantially reduce, c) the fraction of income spent on food would tend to decrease, d) the incidence of obesity- and cardiovascular-related illness may decrease, e) new societal aspirations may emerge in developing countries, where people with rapidly increasing income adopt more optimal dietary consumption patterns, reducing global health risks associated with over consumption, and f) increased agricultural land would become available to support food security goals among the world's most vulnerable populations.

These interactions raise a whole host of questions, associated with improving quality of life and developing competitive advantages, which are likely to become central to the debate on the green economy and its relationship to N₂O mitigation.

8.4.4. Policy instruments to foster change

In this report we have reviewed a wide range of options for technical measures and behavioural change to reduce N₂O emissions. Here we briefly summarize some of the requirements needed to foster these changes.

- Research, development and training are needed to promote the use of innovative NUE techniques in agriculture, aquaculture, waste management, and industry. While there are many techniques that are already known, incentives are needed to promote adoption of available approaches, while training in low N₂O emission approaches is critical.
- Better nitrogen use may be encouraged by avoiding subsidies that encourage nitrogen overuse. Over recent decades, fertilizer subsidies in some countries to meet food security objectives have encouraged over-fertilization, reduced manure recycling and increased pollution, including N₂O emissions. A greater awareness of crop and livestock nutrient needs could allow fertilizer subsidies to be restructured or decreased, reducing N₂O emissions without compromising food

security (Zhang et al., 2013; Sutton et al., 2013a).

- Targeted use of nitrogen subsidies can nevertheless encourage best practices. This is illustrated by the example of the Bangladesh government, which in 2008 wanted to reduce its expenditure on fertilizer subsidy payments in the face of higher fertilizer prices. To reduce the demand for fertilizer and consequently the amount of subsidies, the government strengthened its national programme for using deep soil placement of urea fertilizer (Savant and Stangel, 1990; IFDC, 2012). This reduced fertilizer requirements, ammonia emissions and is expected to have decreased N₂O emissions.
- Options for enabling N₂O mitigation measures include levies, incentives or tradable permits. These could catalyze new markets for improving NUE until they can become self-sustaining. For example, the inclusion of N₂O in existing greenhouse gas emission trading schemes still needs further development (DECC, 2011). Here one can expect an ongoing debate on the relative merit of regulatory, economic and voluntary approaches.
- Where voluntary approaches are favoured, the key is to set clear targets in relation to specific indicators, such as NUE, and to quantify the improvements achieved in relation to these targets (Sutton et al., 2007).
- It is vital to develop communication strategies and tools to encourage N₂O mitigation and wider N management. Promoting the market benefits of Clean-N technologies will encourage environmental competition between businesses. At the same time, better public communication is needed to explain the health, environmental and price benefits of optimizing consumption rates of meat and dairy products (Sutton et al., 2013b).

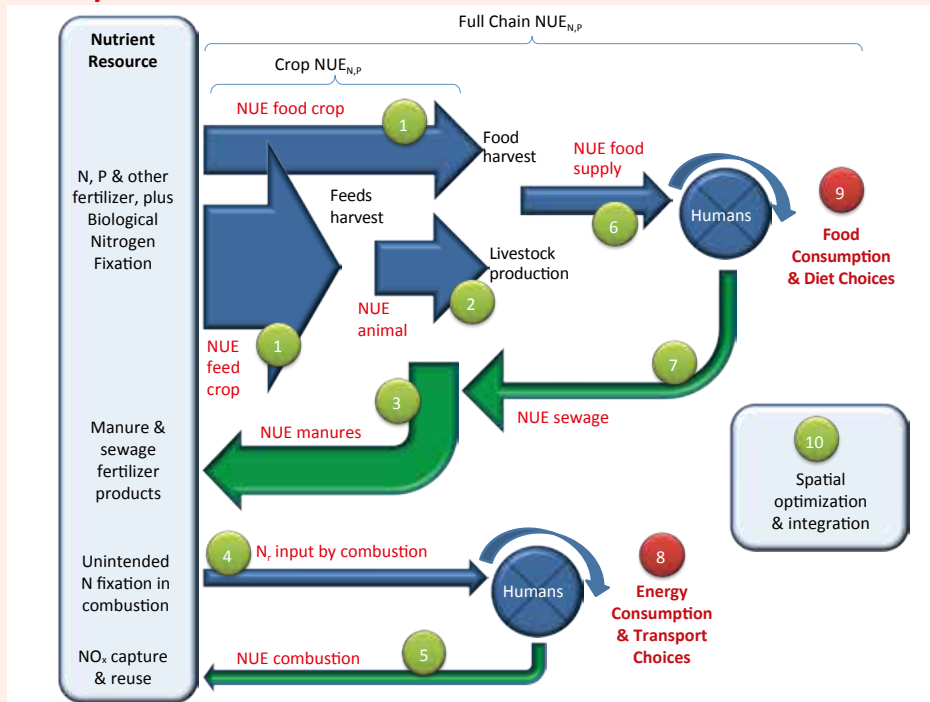
8.5. Embedding N₂O mitigation in international governance

Up to now we have reviewed prospects for mitigating N₂O emissions and examined its links to the green economy and policy instruments to encourage mitigation. Another important aspect of achieving N₂O mitigation is to find the proper governance setting for taking action on its emissions. While there is a wide range of local to national settings for action, here we concentrate on opportunities at the international level. We focus our attention on existing international institutions, as this appears to be the preference of many policymakers (Sutton et al. 2013b).

Given the impacts of N₂O on climate change and ozone layer depletion, we first consider international agreements that address these issues:

United Nations Framework Convention on Climate Change (UNFCCC): N₂O is currently included under the 1997 Kyoto Protocol of the UNFCCC. Some success has been achieved through projects in the nitric and adipic acid and caprolactam production sectors under the Clean Development Mechanism (CDM), with certified emissions reductions (CERs) equivalent to 0.5 Tg N₂O-N issued in 2012 (UNEP, 2013b). However, as noted in Chapter 5, there is some ongoing discussion

Box 8.1: Minimizing N₂O emissions in the context of improving full-chain nitrogen use efficiency.



Nitrous oxide emissions are closely coupled to the overall flow of reactive nitrogen compounds, which can be seen as a cycle from resource through use (blue arrows), with recycling (green arrows). The system is driven by the ‘motors’ of human consumption. Circles highlight ten key actions to increase Full-chain Nitrogen Use Efficiency (NUE), incorporating improved technical efficiency (green circles) and the effects of altered consumption patterns (red circles). Each of these actions offers potential for N₂O mitigation by reducing the overall nitrogen flows required to meet human needs.

(Source: Sutton et al., 2013a).

about possible CO₂ leakage in this sector (Schneider and Kollmus, 2010). Furthermore, there has been scant attention under the CDM to agriculture, the largest anthropogenic N₂O source, due to substantial uncertainties in quantifying emission reductions. Overall, the Convention provides a platform for international action on N₂O that until now has been under-utilized. With a new climate treaty scheduled for 2015, policy-makers have an opportunity to develop a more focused approach to N₂O. This could include:

- (i) CDM reform which incentivizes N₂O reduction in industrial, energy and transport sectors, while minimizing the potential for carbon leakage,
- (ii) emulating the methodologies of several regional agricultural N₂O carbon-offset schemes (e.g. Millar et al. 2010) at the international scale,
- (iii) giving more attention to N₂O reductions within “Land Use, Land Use Change, and Forestry” (LULUCF) activities.

United Nations Vienna Convention for the Protection of the Ozone Layer: The Vienna Convention’s 1987 Montreal Protocol has been very successful in reducing the production and consumption of ozone depleting substances, most notably CFCs (WMO/UNEP, 2011). Given the N₂O threat to the ozone layer (Chapter 2), there is a case for including N₂O within this protocol (Kanter et al., 2013). Policymakers could take advantage of the protocol’s existing infrastructure, including its assessment panels, as well as its well-respected

financial mechanism. One way to integrate N₂O issues into the Protocol would be by setting and monitoring NUE standards (Sutton et al., 2013a,b). Options for action under the Montreal Protocol include:

- (i) setting up a special task force within the Technology and Economics Assessment Panel to review the feasibility of N₂O emission reduction measures across all sectors,
- (ii) controlling N₂O under the Montreal Protocol through nitrogen use efficiency standards.

Given that the mitigation of N₂O links to the entire nitrogen cycle, it also makes sense to consider settings that deal with other related environmental issues. Within these frameworks, N₂O mitigation could become part of a broader nitrogen or nutrient management strategy:

United Nations Convention on Biological Diversity (CBD): Target 8 of the Aichi Biodiversity Targets calls for nutrient pollution reductions to levels “not detrimental to ecosystem system function and biodiversity”. A nitrogen loss indicator has been developed to monitor progress on this goal (Bleeker et al., 2011), and reducing N₂O emissions could become part of a larger effort to reduce nitrogen losses. However, nutrient pollution is a relatively new focus of this convention, the mandate of which already spans very diverse issues. Indeed, the nutrient target is one of 20, making the Convention a potentially interesting, but crowded setting for developing N₂O reduction strategies. Potential next

steps for the Convention include:

- (i) establishing measurable milestones to evaluate the progress of Target 8, and
- (ii) setting up a clearing-house to provide countries with information on options for implementing Target 8.

UNECE Convention on Long Range Transport of Air Pollution (LRTAP): The 1999 Gothenburg Protocol (revised 2012) under the LRTAP sets national limits on NO_x and NH₃ emissions. These controls, in turn, are expected to reduce secondary N₂O emissions through its connections in the nitrogen cycle. LRTAP's Task Force on Reactive Nitrogen focuses on strategies for reducing N pollution, and includes an expert panel on N and climate change. A drawback of LRTAP is its limitation at present to Parties in Europe, Central Asia and North America, not covering countries where much of the growth in N₂O emissions is occurring. Options for next steps include:

- (i) attracting new Parties, with a particular focus on emerging economies with increasing N fertilizer use such as in South and East Asia, and
- (ii) building on the work of the Task Force on Reactive Nitrogen to incorporate N₂O mitigation strategies.

Global Program of Action on the Protection of the Marine Environment from Land-based Activities (GPA): In contrast to the agreements described above, GPA is a non-binding program subject to regular intergovernmental review, which supports regional programs to protect the marine environment. Nutrient management is one of its three focal points, making it directly relevant to N₂O. It has functioned for many years as a very useful clearinghouse for information among many states worldwide. This body could play a key advisory role in implementing N₂O controls, particularly in agriculture. Next steps could include:

- (i) strengthening the role of the GPA to incorporate mitigation of N₂O emissions and other forms of nitrogen pollution (Sutton et al., 2013b), and
- (ii) applying the approach of the Climate and Clean Air Coalition (CCAC) to heighten awareness of nitrogen pollution at high levels of government and create a central forum in which to begin to address it.

Each of these options has specific advantages and drawbacks as a policy setting for N₂O mitigation. Another option is that responsibility for managing N₂O could be shared across several of these agreements, which would require a new coordination mechanism. It is not the task of this report to recommend one policy pathway in particular. Whichever approach policy makers decide to take, the complexities of regulating N₂O should be kept in mind, including interactions with food and energy security, the inequitable distribution of fertilizer use, the diverse nature of farming practices, and the consequences of the nitrogen cascade. In order to motivate action, it will be critical to take into account the multiple benefits of improved nitrogen management and N₂O mitigation.

8.6 Conclusions

- Based on four sets of scenarios, including three published scenarios and a new set of scenarios described

here, concerted mitigation could lead to a decline in anthropogenic N₂O emissions of 22% in 2050 compared with 2005.

- The mitigation scenarios developed in this report show substantially reduced N₂O emissions compared with the BAU in 2050. Whereas BAU emissions of the new scenario set are 8.9 Tg N₂O-N/yr in 2050⁹⁵, the scenario of mitigating industry and biomass burning emissions lowers emissions to 7.6 Tg N₂O-N/yr; efficiency of agricultural production lowers emissions to 5.8 Tg/yr; a combination of efficiency of agricultural production with more efficient consumption (reduced food waste and lower meat consumption) lowers emissions to 4.5 Tg/yr; and a combination of all measures lowers emissions to 3.1 Tg/yr.
- In arable and livestock agriculture, aquaculture and waste management, N₂O measures that focus on improving nitrogen use efficiency (NUE) benefit the green economy by saving nitrogen fertilizer as a valuable resource.
- Reducing excess per capita meat and dairy consumption in the developed world would improve full chain NUE, reducing N₂O and other N emissions, and could foster societal aspirations across the world to avoid levels of livestock consumption significantly in excess of dietary needs. It could simultaneously offer opportunities to reduce the fraction of income spent on food, the incidence of obesity-related illness and the amount of land needed to support food security goals.
- Recent valuation suggests that the total economic benefits to society of improving nitrogen use efficiency substantially exceeds the benefits of taking action to the emitting sectors. The additional benefits to society include reduced threats to human health and ecosystems through improved air, soil and water quality.
- The linking of efficiency savings for some business sectors, especially agriculture, with the wider economic value of less nitrogen pollution provides a strong case for society to reduce N₂O and other forms of nitrogen pollution simultaneously.
- Policy instruments to encourage N₂O mitigation include: capacity building and training in low N₂O emission approaches, avoidance of environmentally damaging nitrogen subsidies, internalizing the price of nitrogen pollution through appropriate levies, abatement subsidies or tradable permits, insurance to manage risks to farmers, and communication to promote the benefits of clean-nitrogen technologies.
- There is currently no single international policy framework leading on N₂O and nitrogen mitigation. Options include strengthening or extending existing agreements and developing improved coordination mechanisms. A key to success in drawing down N₂O emissions will be to demonstrate the multiple benefits to be gained by holistically managing the nitrogen cycle as part of the green economy.

⁹⁵ This BAU value comes from the new scenario set developed in this report and summarized in Table 8.1. It should not be confused with the mean value (9.7) of BAUs from four scenario sets summarized in Table 8.2.

References

Chapter 1

- Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., Asner, G. P., Cleveland, C. C., Green, P. A., Holland, E. A., Karl, D. M., Michaels, A. F., Porter, J. H., Townsend, A. R., Vöosmarty, C. J. (2004) Nitrogen cycles: past, present, and future. *Biogeochemistry*, 70: 153–226
- Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A. (2008) Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. *Science*, 320(5878), 889–892. doi: 10.1126/science.1136674
- Gruber N., Galloway, J.N. (2008) An Earth-system perspective of the global nitrogen cycle. *Nature*, 45, 293–296
- Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A, Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., and Zhang, F.S. (2013) Our Nutrient World: The challenge to produce more food and energy with less pollution. *Global Overview of Nutrient Management*. Centre for Ecology and Hydrology, Edinburgh & United Nations Environment Programme, Nairobi.
- Oenema, O., Bleeker, A., Braathen, N.A., Budňáková, M., Bull, K., Čermák, P., Geupel, M., Hicks, K., Hoft, R., Kozlova, N., Leip, A., Spranger, T., Valli, L., Velthof, G., Winiwarter, W. (2011). Nitrogen in current European policies. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman et al., Cambridge University Press.

Chapter 2

- Ballantyne, A.P., Alden, C.B., Miller, J.B., Tans, P.P., White, J.W.C. (2012) Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature*, 488(7409), 70–72.
- Butterbach-Bahl, K., Gundersen, P., Ambus, P., Augustin, J., Beier, C., Boeckx, P., Dannenmann, M., Gimeno, B.S., Ibrom, A., Kiese, R., Kitzler, B., Rees, R.M., Smith, K.A., Stevens, C., Vesala, T., Zechmeister-Boltenstern, S. (2011) Nitrogen processes in terrestrial ecosystems. In: *The European nitrogen assessment: sources, effects and policy perspectives*. Sutton, M. A., Howard, C. M., & Erisman, J. W. (Eds.). Cambridge University Press.
- Crutzen, P.J. (1970) The influence of nitrogen oxides on the atmospheric ozone content. *Quarterly Journal of the Royal Meteorological Society*, 96(408), 320–325.
- Daniel, J.S., Fleming, E.L., Portmann, R.W., Velders, G.J.M., Jackman, C.H., Ravishankara, A.R. (2010) Options to accelerate ozone recovery: ozone and climate benefits. *Atmospheric Chemistry and Physics*, 10(16), 7697–7707.
- Denman, K.L., Brasseur, A.G., Chidthaisong, P., Ciais, P., Cox, R.E., Dickinson, D., Hauglustaine, C., Heinze, E., Holland, D., Jacob, U., Lohmann, S., Ramachandran, P.L., da Silva Dias, Wofsy, S.C., Zhang, X. (2007). Couplings between changes in the climate system and biogeochemistry. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 499–587
- Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vöosmarty, C.J. (2004) Nitrogen cycles: past, present, and future. *Biogeochemistry*, 70: 153–226.
- Johnston, H. (1971) Reduction of stratospheric ozone by nitrogen oxide catalysts from supersonic transport exhaust. *Science*, 173(3996), 517–522.
- Joos, F., Roth, R., Fuglestedt, J.S., Peters, G.P., Enting, I.G., von Bloh, W., Brovkin, V., Burke, E.J., Eby, M., Edwards, N.R., Friedrich, T., Frölicher, T.L., Halloran, P.R., Holden, P.B., Jones, C., Kleinen, T., Mackenzie, F.T., Matsumoto, K., Meinshausen, M., Plattner, G.K., Reisinger, A., Segsneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A., Weaver, J. (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics*, 13(5), 2793–2825. doi: 10.5194/acp-13-2793-2013
- Joos, F., Spahni, R. (2008). Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. *Proceedings of the National Academy of Sciences*, 105(5), 1425–1430.
- Lamarque, J.F., Kiehl, J.T., Brasseur, G.P., Butler, T., Cameron-Smith, P., Collins, W.D., Collins, W.J., Granier, C., Hauglustaine, D., Hess, P.G., Holland, E.A., Horowitz, L., Lawrence, M.G., McKenna, D., Merilees, P., Prather, M.J., Rasch, P.J., Rotman, D., Shindell, D., Thornton, P. (2005). Assessing future nitrogen deposition and carbon cycle feedback using a multimodel approach: analysis of nitrogen deposition. *Journal of Geophysical Research: Atmospheres*, 110, 1–21.
- MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Elkins, J. (2006). Law Dome CO₂, CH₄ and N₂O ice core records extended to 2000 years BP. *Geophysical Research Letters*, 33(14), L14810. doi: 10.1029/2006GL026152
- Park, S., Croteau, P., Boering, K.A., Etheridge, D.M., Ferretti, D., Fraser, P.J., Kim, K.R., Krummel, P.B., Langenfelds, R.L., van Ommen, T.D., Steele, L.P., Trudinger, C.M. (2012) Trends and seasonal cycles in the isotopic composition of nitrous oxide since 1940. *Nature Geoscience*, 5, 261–265, doi:10/1038/NGEO1421.
- Pinder, R.W., Davidson, E.A., Goodale, C.L., Greaver, T.L., Herrick, J.D., Liu, L. (2012) Climate change impacts of US reactive nitrogen. *Proceedings of the National Academy of Sciences, USA*, 109, 7671–7675. doi: 10.1073/pnas.1114243109.
- Portmann, R.W., Daniel, J.S., Ravishankara, A.R. (2012) Stratospheric ozone depletion due to nitrous oxide: influences of other gases, *Philosophical Trans. Roy. Soc. B*, 367, pp: 1256–1264, doi: 10.1098/rstb.2011.0377.
- Ravishankara, A.R., Daniel, J.S., Portmann, R.W. (2009) Nitrous oxide (N₂O): The dominant ozone-depleting substance emitted in the 21st century. *Science*, 326 (5949), 123–125.
- Ravishankara, A.R., Lovejoy, E.R. (1994) Atmospheric lifetime, its application and its determination: CFC-substitutes as a case study. **Journal of the Chemical Society, Faraday Transactions**, 90, 2159–216. doi: 10.1039/FT9949002159.
- Roeckmann, T., Kaiser, J., Brenninkmeijer, C.A.M. (2003) The isotopic fingerprint of the pre-industrial and the anthropogenic N₂O source. *Atmospheric Chemistry and Physics*, 3, 315–323.
- UNEP (2011) HFCs: A Critical Link in Protecting Climate and the Ozone Layer. United Nations Environment Programme (UNEP), 36 pp.

- Wayne, R.P. (2000). *Chemistry of the Atmosphere*. 3rd Ed, Oxford University Press, 2000.
- WMO (2011) *Scientific Assessment of Ozone Depletion: 2010*, Global Ozone Research and Monitoring Project-Report No. 52, Geneva, Switzerland.
- ### Chapter 3
- Andreae, M. O., Merlet, P. (2001). Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles*, 15, 955-966.
- Beman, J.M., Chow, C.E., King, A.L., Feng, Y., Fuhrman, J.A., Andersson, A., Bates, N.R., Popp, B.N., Hutchins, D.A. (2011) Global declines in oceanic nitrification rates as a consequence of ocean acidification. *Proceedings of the National Academy of Sciences*, 108(1), 208-213. doi: 10.1073/pnas.1011053108
- Bianchi, D., Dunne, J.P., Sarmiento, J.L., Galbraith, E.D. (2012) Data-based estimates of suboxia, denitrification, and N₂O production in the ocean and their sensitivities to dissolved O₂. *Global Biogeochemical Cycles*, 26(2), GB2009. doi:10.1029/2011GB004209
- Creutzig, F., Popp, A., Luderer, G., Minx, J., Edenhofer, O. (2012) Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nature Climate Change*, 2(5), 320-327.
- Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W. (2008) N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics*, 8(2), 389-395.
- Davidson, E.A. (2009) The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience*, 2(9), 659-662.
- Davidson, E.A. (2012) Representative concentration pathways and mitigation scenarios for nitrous oxide. *Environmental Research Letters*, 7(2), 024005.
- Del Grosso, S.J., Wirth, T., Ogle, S.M., Parton, W.J. (2008) Estimating agricultural nitrous oxide emissions. *Eos, Transactions American Geophysical Union*, 89(51), 529-540.
- Denman, K.L., Brasseur G., Chidthaisong A., Ciais, P., Cox, P.M., Dickinson, R.E., Ramachandran, S., da Silva, P.L., Wofsy S.C., Zhanf, X. (2007) Coupling Between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., Qin, D., Manning M., Chen, Z., Marquis, M., Averyt, K.B., Tignor M. Miller (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Duce, R.A., LaRoche, J., Altieri, K., Arrigo, K.R., Baker, A.R., Capone, D.G., Cornell, S., Dentener, F., Galloway, J., Ganeshram, R.S., Geider, R.J., Jickells, T., Kuypers, M.M., Langlois, R., Liss, P.S., Liu, S.M., Middelburg, J.J., Moore, C.M., Nickovic, S., Oeschler, A., Pedersen, T., Prospero, J., Schlitzer, R., Seitzinger, S., Sorensen, L.L., Uematsu, M., Ulloa, O., Voss, M., Ward, B., Zamora L. (2008) Impacts of Atmospheric Anthropogenic Nitrogen on the Open Ocean. *Science*, 320(5878): 893-897. doi: 10.1126/science.1150369
- Dutreuil, S., Bopp, L., Tagliabue, A. (2009) Impact of enhanced vertical mixing on marine biogeochemistry: lessons for geo-engineering and natural variability. *Biogeosciences*, 6, 901-912, doi:10.5194/bg-6-901-2009.
- Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K. (Eds.) (2011) *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press.
- EDGAR (2009). *Emissions Database for Global Atmospheric Research (EDGAR)*, version 4.0. 2009 (<http://edgar.jrc.ec.europa.eu>).
- Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z., Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1(10), 636-639. doi: 10.1038/ngeo325
- Galloway, J. N., Aber, J. D., Erisman, J. W., Seitzinger, S. P., Howarth, R. W., Cowling, E. B., Cosby, B. J. (2003) The nitrogen cascade. *Bioscience*, 53(4), 341-356. doi: 10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2
- Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vöosmarty, C.J. (2004) Nitrogen cycles: past, present, and future. *Biogeochemistry*, 70: 153-226.
- Gruber, N. (2008) The marine nitrogen cycle: Overview of distributions and processes. In: *Nitrogen in the marine environment*. Capone, D.G., Bronk, D.A., Mulholland, M.R., Carpenter, E.J. (Eds.). Elsevier, Amsterdam, 1-50
- Hoefnagels, R., Smeets, E., Faaij, A. (2010) Greenhouse gas footprints of different biofuel production systems. *Renewable and Sustainable Energy Reviews*, 14(7), 1661-1694.
- IPCC. (2007). *Climate Change 2007: Agriculture*. In: Metz B., Davidson O.R., Bosch P.R. (eds). *Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC, 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. <http://www.ipcc-nggip.iges.or.jp/public/2006gl/>
- Keeling, R. F., Körtzinger, A., Gruber, N. (2010) Ocean deoxygenation in a warming world. *Annual Review of Marine Science*, 2, 199-229. doi: 10.1146/annurev.marine.010908.163855
- Law, Y., Ye, L., Pan, Y., Yuan, Z. (2012). Nitrous oxide emissions from wastewater treatment processes. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367, 1265-1277
- Machida, T., Nakazawa, T., Fujii, Y., Aoki, S., Watanabe, O. (1995) Increase in the atmospheric nitrous oxide concentration during the last 250 years. *Geophysical Research Letters*, 22(21), 2921-2924. doi: 10.1029/95GL02822
- Melillo, J.M., Reilly, J.M., Kicklighter, D.W., Gurgel, A.C., Cronin, T.W., Paltsev, S., Felzer, B.S., Wang, X., Sokolov, A.P., Schlosser, C.A. (2009). Indirect emissions from biofuels: how important? *Science*, 326(5958), 1397-1399. doi: 10.1126/science.1180251
- Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., Van Cleemput, O. (1998) Closing the global N₂O budget: nitrous oxide emissions through the agricultural nitrogen cycle. *Nutrient cycling in Agroecosystems*, 52(2-3), 225-248.
- Nakicenovic, N., Swart, R. (2000). *Special report on emissions scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press.
- Pechony, O., Shindell, D. T. (2010) Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences*, 107(45), 19167-19170. doi: 10.1073/pnas.1003669107
- Pinder, R. W., Davidson, E. A., Goodale, C. L., Greaver, T. L., Herrick, J. D., Liu, L. (2012). Climate change impacts of US reactive nitrogen. *Proceedings of the National Academy of Sciences*, 109(20), 7671-7675. doi: 10.1073/pnas.1114243109
- Prather, M., Ehhalt, D., Dentener, F., Derwent, R., Dlugokencky, E., Holland, E., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P., Midgley, P., Wang, M., Bernsten, T., Bey, I., Brasseur, G., Buja, L., Collins, W.J., Daniel, J., DeMore, W.B., Derek, N., Dickerson, R., Etheridge, D., Feichter, J., Fraser, P., Friedl, R., Fuglestvedt, J., Gauss, M., Grenfell, L., Grüber, A., Harris, N., Hauglustaine, D., Horowitz, L., Jackman, C., Jacob, D., Jaeglé, L., Jain, A., Kanakidou, M., Karlsdottir, S., Ko, M., Kurylo, M., Lawrence, M., Logan, J.A., Manning, M., Mauzerall, D., McConnell, J., Mickley, L., Montzka, S., Müller, J.F., Olivier, J., Pickering, K., Pitari, G., Roelofs, G.J., Rogers, H., Rognerud, B., Smith, S., Solomon, S., Staehelin, J., Steele, P., Stevenson, D., Sundet, J., Thompson, A., van Weele, M., von Kuhlmann, R., Wang, Y., Weisenstein, D., Wigley, T., Wild, O., Wuebbles, D., Yantosca, R. (2001). *Atmospheric Chemistry and Greenhouse Gases, in Climate Change 2001: The Scientific Basis. Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton, Y. Ding and D. J. Griggs, pp. 239-287, Cambridge University Press, Cambridge UK
- Schneider, L., Lazarus, M., Kollmuss, A. (2010) *Industrial N₂O Projects Under the CDM: Adipic Acid-A Case of Carbon Leakage?*. Somerville MA: Stockholm Environment Institute.
- Suntharalingam, P., Sarmiento, J.L., Toggweiler, J.R. (2000) Global significance of nitrous-oxide production and transport from oceanic low-oxygen zones: A modeling study. *Global Biogeochemical Cycles*, 14(4), 1353-1370. doi: 10.1029/1999GB900100
- Syakila, A., Kroeze, C. (2011). The global nitrous oxide budget revisited. *Greenhouse Gas Measurement and Management*, 1(1), 17-26. doi: 10.3763/ghgmm.2010.0007
- UNEP (2012). *The emissions gap report 2012*. United Nations Environment Programme (UNEP), Nairobi, Kenya. <http://www.unep.org/publications/ebooks/emissionsgap2012/>
- USEPA (2012) *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions*. EPA 430-R-12-006
- van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., T. Kram, Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., Rose, S. K. (2011a) The representative concentration pathways: an overview. *Climatic Change*, 109(1-2), 5-31.
- van Vuuren, D. P., Stehfest, E., den Elzen, M. G., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Klein, G.K., Hof, A., Mendoza, B.A., Oostenrijk, R., van Ruijven, B. (2011b) RCP2.6: exploring the possibility to keep global mean temperature increase below 2 C. *Climatic Change*, 109(1-2), 95-116.
- ### Chapter 4
- Aguilera, E., Lassaletta, L., Sanz-Cobena, A., Garnier, J., Vallejo, A. (2013) The potential of organic fertilizers and water management to reduce N₂O emissions in Mediterranean climate cropping systems. *A review. Agriculture, Ecosystems & Environment*, 164, 32-52
- Akiyama, H., Yan X., Yagi K. (2010) Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N₂O and NO emissions from agricultural soils: meta-analysis. *Global Change Biology*, 16(6), 1837-1846

- Alexandratos, N., Bruinsma J. (2012) World Agriculture towards 2030/2050, The 2012 revision. ESA Working paper No. 12-03, Rome, FAO.
- Baggs, E.M., Chebii, J., Nduf, J.K. (2006) A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in western Kenya. *Soil Tillage & Research*, 90, 69-76
- Bai, Z.H., Ma, L., Oenema, O., Chen, Q., Zhang F.S. (2013) Nitrogen and phosphorus use efficiencies in dairy production in China. *Journal of Environment Quality*, 42, 990-1001
- Barraclough, P.B., Howarth, J.R., Jones, J., Lopez-Bellido, R., Parmar, S., Shepherd, C.E., Hawkesford, M.J. (2010) Nitrogen efficiency of wheat: genotypic and environmental variation and prospects for improvement. *European Journal of Agronomy*, 33, 1-11
- Bergström, L.F., and Jokela, W.E. (2001) Ryegrass cover crop effects on nitrate leaching in spring barley fertilized with 15NH_4 15NO_3 . *Journal of Environment Quality*, 30, 1659-1667
- Bouwman, A.F., and Boumans, L.J.M. (2002) Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles*, 16, 1058, doi:10.1029/2001GB001811.
- Burney, J.A., Davis S.J., and Lobell D.B. (2010) Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 12052-12057
- Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiesel, R., Zechmeister-Boltenstern, S. (2013) Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Transactions of the Royal Society B: Biological Sciences*, 368(1621) 20130122; doi:10.1098/rstb.2013.0122.
- Cardenas, L.M., Thorman, R., Ashlee, N., Butler, M., Chadwick, D., Chambers, B., Scholefield, D. (2010) Quantifying annual N_2O emission fluxes from grazed grassland under a range of inorganic fertilizer nitrogen inputs. *Agriculture, Ecosystems & Environment*, 136, 218-226
- Cassman, K.G., Dobermann, A., Walters, D.T., and Yang H. (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Reviews of Environment and Resources*, 28, 315-358
- Cassman, K.G., Dobermann, A.R., Walters, D.T. (2002) Agroecosystems, N-use efficiency, and N management. *Ambio*, 31, 132-140
- Chapuis-Lardy, L., Metay, A., Martinet, M., Rabenarivo M., Toucet J., Douzet J.M., Razafimbelo T., Rabehariso L., Rakotoariso J. (2009) Nitrous oxide fluxes from Malagasy agricultural soils. *Geoderma*, 148, 421-427
- Chen, X.P., Cui, Z.L., Vitousek, P.M., Cassman, K.G., Matson, P.A., Bai, J.S., Meng, Q.F., Hou, P., Yue, S.C., Römheld, V., Zhang, F.S. (2011) Integrated soil-crop system management for food security. *Proceedings of the National Academy of Sciences of the United States of America*, 108, 6399-6404
- Coenen, P.W.H.G., van der Maas, C.W.M., Zijlema, P.J., Baas, K., Van den Berghe, A.C.W.M., Biesebeek, J.D., Brandt, A.T., Geilenkirchen, G., Van der Hoek, K.W., Molter, R., Droge, R., Montfoort, J.A., Peek, C.J., Vonk, J., Van den Wyngaert, I. (2012) Greenhouse Gas Emissions in the Netherlands 1990-2010: National Inventory Report 2012. RIVM Report, 680355007.
- Davidson, E.A. (2009) The contribution of manure and fertilizer N to atmospheric nitrous oxide since 1860. *Nature Geoscience*, 2, 659-662
- Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V., and Veldkamp, E. (2000) Testing a conceptual model of soil emissions of nitrous and nitric oxides. *BioScience*, 50, 667-680
- de Klein, C.A.M., Monaghan, R.M., van der Weerden, T.J., Chrystal, J. (2012) Integration of measures to mitigate reactive N loss to the environment. In: *Innovations from sustainable use of N resources*. Proceedings of the 17th international N workshop, 26-29 June 2012, Wexford, Ireland. pp. 257-261
- de Klein, C.A.M., Cameron, K.C., Di, H.J., Rys, G., Monaghan, R.M., and Sherlock, R.R. (2011) Repeated annual use of the nitrification inhibitor dicyandiamide (DCD) does not alter its effectiveness in reducing N_2O emissions from cow urine. *Animal Feed Science and Technology*, 166-167, 480-491
- Doberman, A. (2007) Nutrient use efficiency – measurement and management. Pages 1-28 In: *Fertilizer Best Management Practices. General Principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations*. International Fertilizer Industry Association, Paris, France.
- Doberman, A., Cassman, K.G. (2005) Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. *Science in China Ser. C Life Sciences*, 48, 745-758.
- EC (European Commission). 2013. The nitrates directive. <http://ec.europa.eu/environment/water/water-nitrates/>
- Erismann, J.W., Sutton, M.A., Galloway, J.N., Klimont, Z., Winiwarter, W. (2008) How a century of ammonia synthesis changed the world. *Nature Geosciences* 1, 636-639
- Fujinuma, R., Venterea, R.T., Rosen, C. (2011) Broadcast urea reduces N_2O but increases NO emissions compared with conventional and shallow-applied anhydrous ammonia in a Coarse-Textured soil. *Journal of Environment Quality*, 40, 1806-1815
- Galloway, J. N., Cowling, E. B. (2002). Reactive nitrogen and the world: 200 years of change. *AMBIO: A Journal of the Human Environment*, 31(2), 64-71.
- Garland, G.M., Suddick, E., Burger, M., Horwath, W.R., Six J. (2011) Direct N_2O emissions following transition from conventional till to no-till in a cover cropped Mediterranean vineyard (*Vitis vinifera*). *Agriculture, Ecosystems & Environment*, 144, 423-428
- Good, A.G., Beatty, P.H. (2011) Fertilizing Nature: A tragedy of excess in the commons. *PLoS Biology*, 9, e1001124.
- Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., Meybeck, A. (2011) *Global Food Losses and Food Waste*. FAO, Rome, 38 pp.
- Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., Steeg, J. van de, Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M. (2010) Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science*, 327, 822-825
- Herridge, D.F., Peoples M.B., Boddey R.M. (2008) Global inputs of biological nitrogen fixation in agricultural systems. *Plant Soil* 311, 1-18
- Hirel, B., Tétu, T., Lea, P.J., Dubois, F. (2011) Improving Nitrogen Use Efficiency in Crops for Sustainable Agriculture. *Sustainability*, 3, 1452-1485
- Hoben, J.P., Gehl, R.J., Millar, N., Grace, P.R., Robertson, G.P. (2011) Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. *Global Change Biology*, 17(2), 1140-1152
- Houghton, R.A. (2005) Tropical deforestation as a source of greenhouse gas emissions. In Moutinho, P., Schwarzman, S. (Eds.) *Tropical Deforestation and Climate Change*. Amazon Institute for Environmental Research. Belem, Brazil, pages 13-21
- IPCC (2001) Indirect N_2O emissions from agricultural. IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. http://www.ipccnggip.iges.or.jp/public/gp/bgp/4_6_Indirect_N2O_Agriculture.pdf
- IPCC (2006) Guidelines for National Greenhouse Gas Inventories. <http://www.ipcc-nggip.iges.or.jp/public/2006gl/>
- IPNI (2012) 4R Plant Nutrition: A Manual for Improving the Management of Plant Nutrition. International Plant Nutrition Institute. Norcross, Georgia, USA. ISBN 978-0-9834988-1-0.
- Johnson, J.M.F., Franzluebbers, A.J., Weyers, S.L. (2007) Agricultural opportunities to mitigate greenhouse gas emission. *Environmental Pollution*, 150, 107-124
- Ju, X.T., Lu, X., Gao, Z.L., Chen, X.P., Su, F., Kogge, M., Römheld, V., Christie, P., Zhang, F.S. (2011) Processes and factors controlling N_2O production in an intensively managed low carbon calcareous soil under sub-humid monsoon conditions. *Environmental Pollution*, 159, 1007-1016
- Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., and Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., Zhang F.S. (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences of the United States of America*, 106, 3041-3046
- Kasimir-Klemetsson, Å., Klemetsson, L., Berglund, K., Martikainen, P., Silvola, J., Oenema, O. (1997) Greenhouse gas emissions from farmed organic soils: a review. *Soil Use and Management*, 13, 245-250
- Keller, M., Veldkamp, E., Weitz, A.M., Reiners, W.A. (1993) Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica. *Nature*, 365, 244-246
- Kennedy, T.L., Suddick E.C., Six J. (2013) Reduced Nitrous Oxide Emissions and Increased Yields in California Tomato Cropping Systems under Drip Irrigation and Fertigation. *Agriculture, Ecosystems Environment*, 170, 16-27
- Kros, J., Heuvelink G.B.M., Reinds G.J., Lesschen J.P., Ioannidi V., and de Vries W. (2012) Uncertainties in model predictions of nitrogen fluxes from agro-ecosystems in Europe. *Biogeosciences*, 9, 6051-6094
- Kummu, M., De Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J. (2012) Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Science of the Total Environment* 438, 477-489
- Lanuza, F., Alfaro, A., Muñoz, C., Salazar, F. (2012) Producción animal sustentable. Una mirada retrospectiva y proyección futura. 17 Congreso Chileno de Medicina Veterinaria. Valdivia, Chile, 18-20 de noviembre, pp. 30-49
- Leip, A., Busto, M., Winiwarter, W. (2011) Developing spatially stratified N_2O emission factors for Europe. *Environmental Pollution*, 159(11), 3223-3232
- Lesschen, J. P., Velthof, G. L., de Vries, W., Kros, J. (2011a) Differentiation of nitrous oxide emission factors for agricultural soils. *Environmental Pollution*, 159(11), 3215-3222
- Lesschen, J.P., van den Berg, M., Westhoek, H., Witzke P., Oenema, O. (2011b.) Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science and Technology*, 166-167, 16-28
- Li, L., Zhang, F.S., Li, X.L., Christie, P., Sun, J.H., Yang, S.C., Tang, C.X. (2003)

- Interspecific facilitation of nutrient uptake by intercropped maize and faba bean. *Nutrient Cycling in Agroecosystems*, 65, 61-71
- Lobell, D.B., Cassman, K.G., Field, C.B. (2009) Crop yield gaps: their importance, magnitudes, and causes. *Annual Review of Environment and Resources*, 334, 179-204
- Ma, B.L., Wu, L.T., Tremblay, N., Deen, W., Morrison, M.J., McLaughlin, N.B., Gergorich, E.G., Stewart, G. (2010b.) Nitrous oxide fluxes from corn fields: on-farm assessment of the amount and timing of N fertilizer. *Global Change Biology*, 16, 156-170
- Ma, L., Ma, W.Q., Velthof, G.L., Wang, F.H., Qin, W., Zhang, F.S., and Oenema, O. (2010a.) Modeling Nutrient Flows in the Food Chain of China. *Journal of Environment Quality*, 39, 1279-1289
- Ma, L., Velthof, G.L., Wang, F.H., Qin, W., Zhang, W.F., Liu, Z., Zhang, Y., Wei, J., Lesschen, J.P., Ma, W.Q., Oenema, O., and Zhang F.S. (2012) Nitrogen and phosphorus use efficiencies and losses in the food chain in China at regional scales in 1980 and 2005. *Science of the Total Environment*, 434, 51-61
- Marinho, E.V.A., DeLaune R.D., Lindau C.W. (2004) Nitrous Oxide Flux from Soybeans Grown on Mississippi Alluvial Soil. *Communications in Soil Science and Plant Analysis*, 35, 1-8
- Matson, P.A., Naylor, R., Ortiz-Monasterio, I. (1998) Integration of environmental, agronomic and economic aspects of fertilizer management. *Science*, 280, 112-115
- McSwiney, C.P., Robertson, G.P. (2005) Nonlinear response of N₂O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. *Global Change Biology*, 11, 1712-1719
- Mikkelsen, S. A., Iversen, T. M., Jacobsen, B. H., Kjaer, S.S. (2010) Denmark-EU: the regulation of nutrient losses from intensive livestock operations. In: *Livestock in a changing landscape: regional perspectives*. Gerber, P., Mooney, H., Dijkman, J., Tarawali, S., de Haan, C. (Eds.). Island Press, Washington, DC.
- Millar, N., Robertson, G.P., Grace, P.R., Gehl, R.J., Hoben, J.P. (2010) N fertilizer management for nitrous oxide (N₂O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture. *Mitigation Adaption Strategies Global Change*, 15, 185-204
- Mosier, A.R., Halvorson, A.D., Reule, C.A., Liu X.J. (2006) Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. *Journal of Environment Quality*, 35, 1584-1598
- Mosier, A.R., Syers, J.K., and Freney, J.R. (Eds.) (2004) *Agriculture and the N cycle. Assessing the impacts of fertilizer use on food production and the environment*. Washington (D.C.): SCOPE 65, Island Press, 291 pp.
- Oenema, O., Tamminga, S. (2005) Nitrogen in global animal production and management options for improving nitrogen use efficiency. *Science in China Series C: Life Sciences*, 48, 871-887
- Parfitt, J., Barthel, M., Macnaughton, S. (2010) Food waste within food supply chains; quantification and potential change to 2050. *Philosophical Transactions of the Royal Society B*: 365, 3065-3081
- Philibert, A., Loyce, C., Makowski, D. (2012) Quantifying uncertainties in N₂O emission due to N fertilizer application in cultivated areas. *PLoS one*, 7(11), e50950. doi: 10.1371/journal.pone.0050950
- Powell, J.M., Gourley C.J.P., Rotz, C.A., Weaver, D.M. (2010) Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environmental Science & Policy*, 13, 217-228
- Reay, D.S., Howard, C.M., Bleeker, A. Higgins, P., Smith, K., Rood, T., Theobald, M.R., Cobeña, A.S., Rees, R.M., Moran, D., Reis, S. (2011) Societal choice and communicating the European nitrogen challenge. In: *The European Nitrogen Assessment*. Sutton, M.A., Howard, C.M., Erisman, J.W. Billen, G., Bleeker, A., Greenfeld, P., van Grinsven, H., Grizzetti, B. (Eds.). Cambridge University Press.
- Ren Z.X., 2013. China industry research network. <http://www.chinairn.com>.
- Richardson, D., Felgate, H., Watmough, N., Thomson, A., Baggs, E. (2009) Mitigating release of the potent greenhouse gas N₂O from the N cycle—could enzymic regulation hold the key? *Trends in biotechnology*, 27, 388-397.
- Roberts, T.L. (2007) Right product, right rate, right time and right place ... the foundation of best management practices for fertilizer. [http://www.ipni.net/publication/bettercrops.nsf/0/91607AF3210A609F852579800080C01C/\\$FILE/Better%20Crops%202007-4%20p14.pdf](http://www.ipni.net/publication/bettercrops.nsf/0/91607AF3210A609F852579800080C01C/$FILE/Better%20Crops%202007-4%20p14.pdf)
- Robertson, G.P., and Tiedje, J.M. (1987) Nitrous oxide sources in aerobic soils: Nitrification, denitrification and other biological processes. *Soil Biology and Biochemistry*, 19, 187-193
- Rochette, P., Janzen, H.H. (2005) Towards a revised coefficient for estimating N₂O emissions from legumes. *Nutrient Cycling in Agroecosystems*, 73, 171-179
- Rosenstock, T.S., Liptzin, D., Six, J., and Tomich, T.P. (2013) Nitrogen fertilizer use in California: Assessing the data, trends and a way forward. *California Agriculture*, 67, 68-79.
- Rotz, C.A. (2004) Management to reduce nitrogen losses in animal production. *Journal of Animal Science*, 82 (E. Suppl.), E119–E137.
- Roy, R.N., Misra R.V. (2002) Economic and environmental impact of improved N management in Asian rice-farming systems. In: Sustainable rice production for food security. Proceedings of the 20th Session of the International Rice Commission. Bangkok, Thailand, 23-26 July 2002.
- Rypdal, K., Winiwarter W. (2001) Uncertainties in greenhouse gas emission inventories-evaluation, comparability and implications. *Environmental Science and Policy*, 4, 107-116
- Sanchez-Martin, L., Sanz-Cobena, A., Meijide, A., Quemada, M., and Vallejo, A. (2010) The importance of the fallow period for N₂O and CH₄ fluxes and nitrate leaching in a Mediterranean irrigated agroecosystem. *European Journal of Soil Science*, 61, 710-720
- Scheer, C., Wassmann, R., Kienzler, K., Ibragimov, N., Eschanov, R. (2008) Nitrous oxide emissions from fertilized, irrigated cotton (*Gossypium hirsutum* L.) in the Aral Sea Basin, Uzbekistan: Influence of nitrogen applications and irrigation practices. *Soil Biology Biochemistry*, 40, 290-301
- Schmidt, J.P., DeJoia, A.J., Ferguson, R.B., Taylor, R.K., Young, R.K., Havlin, J.L. (2002) Corn yield response to N at multiple in-field locations. *Agronomy Journal*, 94, 798-806
- Schröder, J. (2005) Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. *Bioresource Technology*, 96, 253-261
- Shoji, S., Delgado, J., Mosier, A., Miura, Y. (2001) Use of controlled release fertilizers and nitrification inhibitors to increase N use efficiency and to conserve air and water quality. *Communication of Soil Science Plant Analysis*, 32, 1051-1070
- Smil, V. (2000) *Feeding the world. A challenge for the twenty-first century*. MIT Press, Cambridge, Massachusetts, USA.
- Smith, K.A. (Ed.) (2010) *Nitrous Oxide and Climate Change*, Earthscan, London.
- Smith, P., Haberl, H., Popp, A., Erb, K.H., Lauk, C., Harper, R., Tubiello, F.N., Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsidig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo-Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I. Rose S. (2013) How much land based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, 19, 2285-2302
- Smith, P., Martino, D., Cai, Z.C. Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan G.X., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J. (2008) Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363, 789-813
- Snyder, C.S. Bruulsema, T.W. (2007) Nutrient Use Efficiency and Effectiveness in North America: Indices of Agronomic and Environmental Benefit. [http://www.ipni.net/ipniweb/portal.nsf/0/d58a3c2deca9d7378525731e006066d5/\\$FILE/Revised%20NUE%20update.pdf](http://www.ipni.net/ipniweb/portal.nsf/0/d58a3c2deca9d7378525731e006066d5/$FILE/Revised%20NUE%20update.pdf)
- Snyder, C.S., Fixen P.E. (2012) Plant nutrient management and risks of nitrous oxide emission. *Journal of Soil and Water Conservation*, 67, 137-144
- Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E. (2009) Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems and Environment*, 133(3-4), 247-266
- Sperow, M., Eve M., Paustian K. (2003) Potential soil C sequestration on US agricultural soils. *Climatic Change*, 57, 319-339. doi: 10.1023/A:102288832630
- Stehfest, E., and Bouwman, L. (2006) N₂O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems*, 74, 207-228
- Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C. (2006) *Livestock's long shadow: environmental issues and options*. Rome: Food and Agriculture Organization.
- Steinfeld, H., Mooney, H., Schneider, F. Neville L.E. (Eds.) (2010) *Livestock in a changing landscape: Drivers, Consequences and Responses*. Washington, DC: Island Press, 396 pp.
- Subbarao, G.V., Nakahara, K., Hurtado, M.P., Ono, H., Moreta, D. E., Salcedo, A.F., Yoshihashi, A.T., Ishikawa, T., Ishitani, M., Ohnishi-Kameyama, M., Yoshida, M., Rondon, M., Rao, I.M., Lascano, C.E., Berry, W.L., Ito, O. (2009) Evidence for biological nitrification inhibition in *Brachiaria* pastures. *Proceedings of the National Academy of Sciences*, 106(41), 17302-17307. doi: 10.1073/pnas.0903694106.
- Subbarao, G.V., Sahrawat, K.L., Nakahara, K., Rao, I.M., Ishitani, M., Hash, C.T., Kishii, M., Bonnett, D.G., Berry, W.L., Lata, J.C. (2013) A paradigm shift towards low-nitrifying production systems: the role of biological nitrification inhibition (BNI). *Annals of Botany* 112, 297-316
- Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A, Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., Zhang, F.S. (2013) Our Nutrient World: The challenge to produce more food and energy with less pollution. *Global Overview of*

- Nutrient Management. Centre for Ecology and Hydrology, Edinburgh & United Nations Environment Programme, Nairobi.
- Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.) (2011a.) The European Nitrogen Assessment. Sources, Effects and Policy Perspectives. Cambridge University Press, UK.
- Sutton, M.A., Oenema, O., Erisman, J.W., Leip, A., van Grinsven, H., Winiwarer, W. (2011b.) Too much of a good thing. *Nature* 472(7342), 159-161. doi:10.1038/472159a
- Sylvester-Bradley, R., Kindred, D.R. (2009) Analyzing N responses of cereals to prioritize routes to the improvement of N use efficiency. *Journal of Experimental Botany*, 60, 1939-1951
- Tenuta, M., and Beauchamp, E.G. (2003) Nitrous oxide production from granular N fertilizers applied to a silt loam soil. *Canada Journal of Soil Science*, 83, 521-532
- Thomson, A.J., Giannopoulos, G., Pretty, J., Baggs, E.M., Richardson, D.J. (2012) Biological sources and sinks of nitrous oxide and strategies to mitigate emissions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367, 1157-1168
- UNECE (2013) Guidance Document for Preventing and Abating Ammonia Emissions from Agricultural Sources. United Nations Economic Commission for Europe, Executive Body for the Convention on Long-range Transboundary Air Pollution. ECE/EB.AIR/2012/L.9.
- UNEP (2012) Avoiding future famines: Strengthening the ecological foundation of food security through sustainable food systems. <http://www.unep.org/publications/ebooks/avoidingfamines/>
- van Groenigen, J.W., Velthof G.L., Oenema O., Van Groenigen K.J., Van Kessel C. (2010) Towards an agronomic assessment of N₂O emissions: a case study for arable crops. *European Journal of Soil Science*, 61, 903-913
- Velthof, G.L., Brader, A.B., and Oenema, O. (1996) Seasonal variations in nitrous oxide losses from managed grasslands in The Netherlands. *Plant and Soil*, 181, 263-274
- Velthof, G.L., Lesschen, J.P., Webb, J., Pietrzak, S., Miatkowski, Z., Pinto, M., Kros, J., Oenema, O. (2013) The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000-2008. *Science of Total Environment* (in press).
- Venterea, R.T., Dolana M.S., Ochsner T.E. (2010) Urea decreases nitrous oxide emissions compared with anhydrous ammonia in a Minnesota corn cropping system. *Soil Science Society of America Journal*, 72, 407-418
- Venterea, R.T., Halvorson A.D., Kitchen N., Liebig M.A., Cavigelli M.A., Grosso S.J.D., Motavalli P.P., Nelson K.A., Spokas K.A., Singh B.P., Stewart C.E., Ranaivoson A., Strook J., Collins H. (2012) Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. *Frontiers in Ecology and the Environment*, 10, 562-570
- Venterea, R.T., Maharjan B., Dolan M.S. (2011) Fertilizer source and tillage effects on yield-scaled nitrous oxide emissions in a corn cropping system. *Journal of Environment, Quality*, 40, 1521-1531
- Verchot, L.V., Davidson, E.A., Cattânio, H., Ackerman, I.L., Erickson, H.E., Keller, M. (1999) Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia. *Global Biogeochemical Cycles*, 13, 31-46
- Vistoso, E., Alfaro, M., Saggari, S., Salazar, F. (2012) Effect of nitrogen inhibitors on nitrous oxide emissions and pasture growth following an autumn application in a volcanic soil. *Chilean Journal of Agriculture Research*, 72(2), 133-139.
- Wang, G.H., Dobermann, A., Witt, C., Sun, Q.Z., Fu, R.X. (2001) Performance of site specific nutrient management for irrigated rice in Southeast China. *Agronomy Journal*, 93, 869-878
- Weiske, A., Vabitsch, A., Olesen, J. E., Schelde, K., Michel, J., Friedrich, R., Kaltschmitt, M. (2006) Mitigation of greenhouse gas emissions in European conventional and organic dairy farming. *Agriculture Ecosystems and Environment*, 112, 221-232
- Westhoek, H., Rood, T., van de Berg, M., Janse, J., Nijdam, D., Reudink, M., Stehfest, E. (2011) The protein puzzle: the consumption and production of meat, dairy and fish in the European Union. The Hague: PBL Netherlands Environmental Assessment Agency.
- WHO (2007) Protein and Amino Acid Requirements in Human Nutrition. WHO, Geneva.
- Zhang, F.S., Li, L. (2003) Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant Soil*, 248, 305-312
- Zhang, W.F., Dou, Z.X., He, P., Ju, X.T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.L., Zhang, Y., Wu, L., Chen, X.P., Cassman, K.G., Zhang, F.S. (2013) New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *Proceedings of the National Academy of Sciences of the United States of America*, 110(21), 8375-8380
- 01-0857, SAE, Warrendale, PA.
- Berges, M.G.M., Hofmann, R.M., Scharffe, D., Crutzen, P.J. (1993) Nitrous oxide emissions from motor vehicles in tunnels and their global extrapolation. *Journal of Geophysical Research*, 98, 18527-18531
- Dasch, J.M. (1992) Nitrous oxide emissions from vehicles. *Journal of the Air & Waste Management Association*, 42(1), 63-67. doi: 10.1080/10473289.1992.10466971
- de Jager, D., Hendriks, C.A., Byers, C., van Brummelen, M., Petersdorff, C., Straker, A.H.M., Blok, K., Oonk, J., Gerbens, S., Zeeman, G. (2001) Emission Reduction of Non-CO₂ Greenhouse Gases. Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094
- De Soete, G. (1997) N₂O emissions from combustion and industry. In: Becker, K. H., Wiesen, P. (Eds.) *Proceedings of 7th International Workshop on Nitrous Oxide Emissions*, Cologne, 21-23 April 1997, Report No 41, Bergische Universität Gesamthochschule, Wuppertal, Germany, pp11-13
- Ecofys/Fraunhofer Institute/Okö-Institut (2009) Methodology for the free allocation of emission allowances in the EU ETS post 2012. Sector report for the chemical industry. http://ec.europa.eu/clima/policies/ets/cap/allocation/docs/bm_study-chemicals_en.pdf
- EIA (US Energy Information Administration) (2011) Emissions of greenhouse gases in the United States 2009. http://www.eia.gov/environment/emissions/ghg_report/pdf/0573%282009%29.pdf
- European Commission (2006) World energy technology outlook -2050. European Commission, Brussels, ISBN: 92-79-01636-9.
- Graham, L.A., Belisle, S.L., Rieger, P. (2009) Nitrous oxide emissions from light duty vehicles. *Atmospheric Environment*, 43, 2031-2044
- Groves, M., Sasonow, A. (2009) Uhde EnvINO[®] Technology for NO_x and N₂O abatement – A contribution to reducing emissions from nitric acid plants. Fifth International Symposium on Non-CO₂ Greenhouse Gases (NCGG-5), June 30 to July 3, 2009, Wageningen, Netherlands. http://uhdeftp.de/cgi-bin/byteserver.pl/archive/upload/uhde_publications_pdf_en_15000012.00.pdf
- Hayhurst, A. N., Lawrence, A.D. (1992) Emissions of nitrous oxide from combustion sources. *Prog. Energy Combust. Sci.*, 18, 529-552
- Heland, J., Schäfer, K. (1998) Determination of major combustion products in aircraft exhausts by FTIR emission spectrometry. *Atmospheric Environment*, 32, 3067-3072
- Hupa, M., Matinlinna, J. (Eds.) (1994) *Proceedings of 6th International Workshop on Nitrous Oxide Emissions*, Turku, Finland, 7-9 June.
- IEA (2000) Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide, Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom.
- IHS (2013) <http://www.ihs.com/products/chemical/planning/ceh/nitric-acid.aspx>
- IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Eggleston, S., L. Buendia, K. Miwa, T. Ngara, K. Tanabe (Eds.). Intergovernmental Panel on Climate Change, IGES, Hayama, Kanagawa, Japan.
- JRC (2013) EDGAR. Emission database for global atmospheric research, European Commission Joint Research Centre, Ispra <http://edgar.jrc.ec.europa.eu/index.php>
- Kanter, D., Mauzerall, D. L., Ravishankara, A. R., Daniel, J. S., Portmann, R. W., Grabel, P. M., Moomaw, W. R., Galloway, J. N. (2013) A post-Kyoto partner: considering the stratospheric ozone regime as a tool to manage nitrous oxide. *Proceedings of the National Academy of Sciences*. doi: 10.1073/pnas.122231110.
- Khalek, I.A., Banks, M., Merritt, P. M., Tennent, C., Bailey, B., Greenbaum, D., Shaikh, R., van Moon, A., French, T. (2013) Results from ACES Phase 2: Emissions characterization from 2010 compliant engines, 2013 Health Effects Annual Conference, <http://www.healtheffects.org/annual.htm>
- Khalek, I.A., Bougher, T. L., Merritt, P. M. (2009) Phase 1 of the Advanced Collaborative Emissions Study, CRC Report: ACES Phase 1, <http://www.crao.com/publications/emissions/index.html>
- Khalek, I.A., Bougher, T. L., Merritt, P. M., Zielinska, B. (2011) Regulated and Unregulated Emissions from Highway Heavy-Duty Diesel Engines Complying with United States Environmental Protection Agency 2007 Emissions Standards. *J. Air & Waste Manage. Assoc.*, 61, 427-442
- Koike, N., Odaka, M., Suzuki, H. (1999) Reduction of N₂O from automobiles equipped with three-way catalyst – analysis of N₂O increase due to catalyst deactivation. SAE technical paper no. 1999-0-1081, SAE International, Warrendale, PA.
- Kollmuss, A., Lazarus, M. (2010) Industrial N₂O projects under CDM: the case of nitric acid production. Stockholm Environment Institute (SEI), WP-US-1007.
- Leckner, B., Åmand, L.E. (1992) N₂O emissions from combustion in circulating fluidized bed. In: *Proceedings of 5th International Workshop on Nitrous Oxide Emissions*, Tsukuba, Japan, 1-3 July 1992, ppKL-6-1-KL-6-15.
- Michaels, H. (1998) Emission of nitrous oxide from highway mobile sources.

Chapter 5

- Baronick, J., Heller, B., Lach, G., Ramacher, B. (2000) Impact of sulfur in gasoline on nitrous oxide and other exhaust gas components. Society of Automotive Engineers (SAE). Technical Paper No. 2000-

- Report EPA420-R-98-009, US EPA, Washington DC.
- Odaka, M., Koike, N., Ishii, H., Suzuki, H., Goto, Y. (2002) N₂O emissions from vehicles equipped with three-way catalysts in a cold climate. SAE technical paper no. 2002-01-1717, SAE International, Warrendale, PA.
- Owen, B., Lee, D.S., Lim, L. (2010) Flying into the future: Aviation emissions scenarios to 2050. *Environmental Science and Technology*, 44, 2255–2260
- Schneider, L., Lazarus, M., Kollmuss, A. (2010) Industrial N₂O projects under CDM: adipic acid – a case of carbon leakage? Stockholm Environment Institute (SEI), WP-US-1006.
- SETatWork (Sustainable Energy Technology at Work) (2009). SETatWork good practice: Lanxess AG: redundant thermal decomposition of residual nitrous oxide (N₂O). http://www.setatwork.eu/downloads/SGP22_DE_N2O_Lanxess.pdf
- Shimizu, A., Tanaka, K., Fujimori, M. (2000) Abatement technologies for N₂O emissions in the adipic acid industry, *Chemosphere – Global Change Science*, 2, 425–434
- Siegl, W.O., Korniski, T.J., Richert, J.F.O., Chladek, E., Weir, J.E., Jensen, T.E. (1996) A comparison of the emissions from a vehicle in both normal and selected malfunctioning operation modes. SAE technical paper no. 961903, SAE International, Warrendale, PA.
- Sjödin, A., Cooper, D.A., Andréasson, K. (1995) Estimations of real-world N₂O emissions from road vehicles by means of measurements in a traffic tunnel. *Journal of the Air and Waste Management Association*, 45, 186–190
- Smith, L.R., Carey, P.M. (1982) Characterization of exhaust emissions from high mileage catalyst-equipped automobiles. SAE technical paper no. 820783, SAE International, Warrendale, PA.
- Tsupari, E., Monni, S., Tormonen, K., Pellikka, T., Syri, S. (2007) Estimation of annual CH₄ and N₂O emissions from fluidised bed combustion: an advanced measurement-based method and its application to Finland. *Greenhouse Gas Control* 1(3), 289–297
- UNEP (2011) Bridging the Emissions Gap. United Nations Environment Programme. <http://www.unep.org/publications/ebooks/bridgingemissionsgap/>
- USEPA (United States Environmental Protection Agency) (2004) Update of methane and nitrous oxide emission factors for on-highway vehicles. Report EPA420-P-04-016, Washington DC.
- USEPA (United States Environmental Protection Agency) (2006) Global Mitigation of Non-CO₂ greenhouse gases. Report EPA 430-R-06-005, Washington DC.
- USEPA (United States Environmental Protection Agency) (2012) Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions, EPA 430-R-12-006, Washington DC.
- Wallington, T.J., Sullivan, J.L., Hurley, M.D. (2008). Emissions of CO₂, CO, NO_x, HC, PM, HFC-134a, N₂O and CH₄ from the global light duty vehicle fleet. *Meteorologische Zeitschrift*, 17, 109–116.
- WBCSD (2004) World Business Council for Sustainable Development, Mobility 2030: IEA/SMP Transport <http://www.wbcsd.org/web/publications/mobility/smp-model-document.pdf>
- Wiesen, P. (2010) Abiotic nitrous oxide sources: Chemical industry and mobile and stationary combustion systems. In Smith, K. (Ed.) *Nitrous oxide and climate change*. Earthscan, London.
- Wiesen, P., Kleffmann, J., Kurtenbach, R., Becker, K.H. (1994) Nitrous oxide and methane emissions from aero engines. *Geophysical Research Letters*, 21, 2027–2030
- Wiesen, P., Kleffmann, J., Kurtenbach, R., Becker, K.H. (1996) Emission of nitrous oxide and methane from aero engines: monitoring by tunable diode laser spectroscopy. *Infrared Physics and Technology*, 37, 75–81
- Chapter 6**
- Andrae, M., Merlet, P. (2001) 'Emission of trace gases and aerosols from biomass burning'. *Global Biogeochemical Cycles*, 15(4):955–966
- Aragao, L.E.O.C., Shimabukuro, Y.E. (2010) 'The Incidence of Fire in Amazonian Forests with Implications for REDD'. *Science*, 328(5983):1275–1278
- Berrueta, V.M., Edwards, R.D., Masera, O.R. (2008) Energy performance of wood-burning cookstoves in Michoacan, Mexico. *Renewable Energy*, Volume 33, Issue 5, 859–870, Epidemiology Department, School of Medicine, University of California at Irvine, CA, USA.
- Bhattacharya, S.C., Abdul Salam, P. (2002) Low greenhouse gas biomass options for cooking in the developing countries. *Biomass and Bioenergy*, Volume 22, Issue 4, 305–317
- Cook, G.D., Meyer, C.P. (2009) Fires, fuels and greenhouse gases. In: *Culture, ecology and economy of fire management in North Australian savannas: rekindling the Wurrk tradition*. Russell-Smith, J., Whitehead, P., Cooke, P. (Eds.). CSIRO PUBLISHING.
- Davidson, E.A., De Abreu SÁ, T.D., Reis Carvalho, C.J., De Oliveira Figueiredo, R., Kato, M. d. S. A., Kato, O. R., Ishida, F.Y. (2008) An integrated greenhouse gas assessment of an alternative to slash-and-burn agriculture in eastern Amazonia. *Global Change Biology* 14(5): 998-1007.
- Fernandes, S. D., Trautmann, N. M., Streets, D. G., Roden, C. A., Bond, T. C. (2007) Global biofuel use, 1850–2000. *Global Biogeochemical Cycles*, 21(2). doi: 10.1029/2006GB002836
- Flannigan, M., Cantin, A.S., de Groot, W.J., Wotton, M., Newbery, A., Gowman, L. M. (2013) Global wildland fire season severity in the 21st century. *Forest Ecology and Management*, 294(0), 54-61. doi: 10.1016/j.foreco.2012.10.022.
- García-Frapolli, E., Schilmann, A., Berrueta, V. M., Riojas-Rodríguez, H., Edwards, R.D., Johnson, M., Guevara-Sanginés, A., Armendariz, C., Masera, O. (2010). Beyond fuelwood savings: Valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico. *Ecological Economics*, 69, 2598–2605.
- Giglio, L., Randerson, J.T., Werf, G.R., Kasibhatla, P.S., Collatz, G.J., Morton, D.C., DeFries, R. S. (2010). Assessing variability and long-term trends in burned area by merging multiple satellite fire products. *Biogeosciences*, 7(3), 1171-1186. doi: 10.5194/bg-7-1171-2010
- Korontzi, S., Justice, C. Scholes, R. (2003) Influence of timing and spatial extent of savanna fires in southern Africa on atmospheric emissions. *Journal Of Arid Environments*, 54(2), 395–404
- Masera, O., Edwards, R., Arnez, C. A., Berrueta, V., Johnson, M., Bracho, L. R., Riojas-Rodríguez, H., Smith, K. R. (2007) Impact of Patsari improved cookstoves on indoor air quality in Michoacán, Mexico. *Energy for Sustainable Development*, 11(2), 45-56.
- Meyer, C. P., Cook, G. D., Reisen, F., Smith, T. E. L., Tattaris, M., Russell-Smith, J., Maier, S. W., Yates, C. P., Wooster, M. J. (2012) Direct measurements of the seasonality of emission factors from savanna fires in northern Australia. *Journal of Geophysical Research: Atmospheres* 117(D20): D20305. doi: 10.1029/2012JD017671
- Nepstad, D., Soares-Filho, B. S., Merry, F., Lima, A., Moutinho, P., Carter, J., Bowman, M., Cattaneo, A., Rodrigues, H., Schwartzman, S., McGrath, D.G., Stickler, C.M., Lubowski, R., Piris-Cabezas, P., Rivero, S. Alencar, A., Almeida, O., Stella, O. (2009). The end of deforestation in the Brazilian Amazon. *Science*, 326(5958), 1350-1351.
- Russell-Smith, J., Cook, G. D., Cooke, P. M., Edwards, A. C., Lendrum, M., Meyer, C. P., Whitehead, P. J. (2013). Managing fire regimes in north Australian savannas: applying Aboriginal approaches to contemporary global problems. *Frontiers in Ecology and the Environment*, 11(s1), e55-e63.
- Smith, K.R., Uma, R., Kishore, V.V.N., Zhang, J., Joshi, V., Khalil, M. A. K. (2000) Greenhouse implications of household stoves: an analysis for India. *Annual Review of Energy and the Environment*, 25(1), 741-763.
- UNEP 2011. Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers, United Nations Environment Programme (UNEP), Nairobi, Kenya. http://www.unep.org/pdf/Near_Term_Climate_Protection_&_Air_Benefits.pdf
- UNEP/WMO 2011. Integrated Assessment of black carbon and tropospheric ozone. United Nations Environment Programme (UNEP) / World Meteorological Organization (WMO). http://www.unep.org/dewa/portals/67/pdf/BlackCarbon_report.pdf
- USEPA 2010. Methane and Nitrous Oxide Emissions From Natural Sources. United States Environmental Protection Agency, Office of Atmospheric Programs (6207J) EPA 430-R-10-001, Washington, DC 20460. <http://www.epa.gov/outreach/pdfs/Methane-and-Nitrous-Oxide-Emissions-From-Natural-Sources.pdf>
- van de Werf, G.R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R.S., Jin, Y., van Leeuwen, T.T. (2010) Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmospheric Chemistry and Physics*, 10(23), 11707-11735.
- Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W. (2006) Warming and earlier spring increase western US forest wildfire activity. *Science*, 313(5789), 940-943.
- WHO (World Health Organization) (2006). Fuel for life. Household energy and health. <http://www.who.int/indoorair/publications/fuelforlife.pdf>
- Yevich, R., Logan, J. A. (2003) An assessment of biofuel use and burning of agricultural waste in the developing world. *Global Biogeochemical Cycles*, 17(4), 1095.
- Chapter 7**
- Abreu, M.H., Varela, D.A., Henriquez, L., Villarreal, A., Yarish, C., Sousa-Pinto, I., Buschmann, A.H. (2009) Traditional vs. Integrated Multi-Trophic Aquaculture of *Gracilaria chilensis* C. J. Bird, J. McLachlan & E. C. Oliveira: Productivity and physiological performance. *Aquaculture* 293, 211-220
- Ahmed, M., Dey, M.M., Garcia, Y.T. (2007) Role of species and systems in the development and growth of aquaculture in Asia: needs and prospects. In: Leung, P.S., Lee, Ch.-S., O'Bryen, P.J. (Ed.), *Species and system selection, for sustainable aquaculture*. Blackwell, Ames, Iowa.
- Ahn, J.H., Kim, S., Park, H., Rahm, B., Pagilla, K., Chandran, K. (2010) N₂O emissions from activated sludge processes, 2008-2009: Results of a national monitoring survey in the United States. *Environmental*

- Science and Technology 44, 4505-4511
- Alcamo, J., Van Vuuren, D., Cramer, W. (2006) Changes in ecosystem services and their drivers across the scenarios. In: Carpenter, S.R., Pingali, P.L., Bennett, E.M., Zurek, M.B. (Eds.), *Ecosystems and human well-being: scenarios*. Island Press, Washington, D.C., 279-354
- Barrington, K., Chopin, T., Robinson, S. (2009) Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In: Soto, D. (Ed.), *Integrated mariculture: a global review*. FAO Fisheries and Aquaculture Technical Paper, Rome, 7-46
- Bergheim, A., Brinker, A. (2003) Effluent treatment for flow through systems and European environmental regulations. *Aquacultural Engineering* 27, 61-77
- Bouwman, A.F., Beusen, A.H.W., Overbeek, C.C., Bureau, D.P., Pawlowski, M., Glibert, P.M. (2013) Hindcasts and future projections of global inland and coastal nitrogen and phosphorus loads due to finfish aquaculture. *Reviews in Fisheries Science* 21, 112-156
- Bouwman, A.F., Pawlowski, M., Liu, C., Beusen, A.H.W., Shumway, S.E., Glibert, P.M., Overbeek, C.C. (2011) Global Hindcasts and Future Projections of Coastal Nitrogen and Phosphorus Loads Due to Shellfish and Seaweed Aquaculture. *Reviews in Fisheries Science* 19, 331-357
- Bureau, D.P., Hua, K. (2010) Towards effective nutritional management of waste outputs in aquaculture, with particular reference to salmonid aquaculture operations. *Aquaculture Research* 41, 777-792
- Chandran, K., Stein, L.Y., Klotz, M.G., Van Loosdrecht, M.C.M. (2011) Nitrous oxide production by lithotrophic ammonia-oxidizing bacteria and implications for engineered nitrogen-removal systems. *Biochemical Society Transactions* 39, 1832-1837.
- Crab, R., Avnimelech, Y., Defoirdt, T., Bossier, P., Verstraete, W. (2007). Nitrogen removal techniques in aquaculture for a sustainable production. *Aquaculture*, 270, 1-14
- Delgado, C.L., Wada, N., Rosegrant, M.W., Meijer, S., Ahmed, M. (2003) *Fish to 2020: Supply and demand in changing global markets*. International Food Policy and Research Institute and World Fish Center, Washington, D.C., Penang, Malaysia.
- Diaz, R.J., Rosenberg, R. (2008) Spreading dead zones and consequences for marine ecosystems. *Science* 321, 926-929 (doi: 910.1126/science.1156401).
- EEC (1986) Council directive 1986/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. European Economic Community, Brussels.
- EEC (1991) Directive 1991/271/EEC concerning urban waste water treatment. European Economic Community, Brussels.
- FAO (2012) FAOSTAT database collections. Food and Agriculture Organization of the United Nations, Rome. <http://faostat3.fao.org/home/index.html>
- Freing, A., Wallace, D.W.R., Bange, H.W. (2012) Global oceanic production of nitrous oxide. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367, 1245-1255
- Gross, A., Boyd, C.E., Wood, C.W. (2000) Nitrogen transformations and balance in channel catfish ponds. *Aquacultural Engineering* 24, 1-14
- Hernández, I., Martínez-Aragón, J.F., Tovar, A., Pérez-Lloréns, J.L., Vergara, J.J. (2002) Biofiltering efficiency in removal of dissolved nutrients by three species of estuarine macroalgae cultivated with sea bass (*Dicentrarchus labrax*) waste waters 2. Ammonium. *Journal of Applied Phycology* 14, 375-384.
- Hu, Z., Lee, J.W., Chandran, K., Kim, S., Sharma, K., Brotto, A.C., Khanal, S.K., 2013. Nitrogen transformations in intensive aquaculture system and its implication to climate change through nitrous oxide emission. *Bioresource Technology* 130, 314-320.
- IFPRI, 2003. Outlook for fish to (2020) meeting global demand. In: Delgado, C.L., Wada, N., Rosegrant, M.W., Meijer, S., Ahmed, M. (Ed.). *WorldFish Center*, Penang, Malaysia, p. 28.
- IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC NGGIP Programme, IPCC-TSU/IGES. Published by the Institute for Global Environmental Strategies (IGES), Hayama, Japan on behalf of the IPCC, Hayama, Japan.
- Kampschreur, M.J., Temmink, H., Kleerebezem, R., Jetten, M.S.M., van Loosdrecht, M.C.M. (2009) Nitrous oxide emission during wastewater treatment. *Water Research* 43, 4093-4103
- Kumar, M.S., Burgess, S.N., Luu, L.T. (2004) Review of nutrient management in freshwater polyculture. *Journal of Applied Aquaculture* 16, 17-44
- Langergraber, G., Muellegger, E. (2005) Ecological Sanitation—a way to solve global sanitation problems? *Environment International* 31, 433-444
- Law, Y., Ye, L., Pan, Y., Yuan, Z. (2012) Nitrous oxide emissions from wastewater treatment processes. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367, 1265-1277
- Matthews, H.D., Weaver, A.J., Meissner, K.J., Gillett, N.P., Eby, M. (2004) Natural and anthropogenic climate change: Incorporating historical land cover change, vegetation dynamics and the global carbon cycle. *Climate Dynamics* 22, 461-479
- Michielsens, C.G.J., Lorenzen, K., Phillips, M.J., Gauthier, R. (2002) Asian carp farming systems: Towards a typology and increased resource use efficiency. *Aquaculture Research* 33, 403-413
- Morée, A.L., Beusen, A.H.W., Bouwman, A.F., Willems, W.J. (2013) Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century. *Global Biogeochemical Cycles* 27, doi:10.1002/gbc.20072.
- Naqvi, S.W.A., Bange, H.W., FarÃ-As, L., Monteiro, P.M.S., Scranton, M.I., Zhang, J. (2010) Marine hypoxia/anoxia as a source of CH₄ and N₂O. *Biogeosciences* 7, 2159-2190
- Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigel, M., Yarish, C. (2004) Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* 231, 361-391
- NRC (2011) Nutritional requirements of fish and shrimp. The National Academies Press, Washington, D.C.
- Ridler, N., Wowchuk, M., Robinson, B., Barrington, K., Chopin, T., Robinson, S., Page, F., Reid, G., Szemerda, M., Sewuster, J., Boyne-Travis, S. (2007) Integrated multi-trophic aquaculture (IMTA): A potential strategic choice for farmers. *Aquaculture Economics and Management* 11, 99-110
- Seitzinger, S.P., Mayorga, E., Bouwman, A.F., Kroeze, C., Beusen, A.H.W., Billen, G., Van Drecht, G., Dumont, E., Fekete, B.M., Garnier, J., Harrison, J., Wisser, D., Wollheim, W.M. (2010) Global River Nutrient Export: A Scenario Analysis of Past and Future Trends. *Glob Biogeochem Cycles*, 23, doi:10.1029/2009GB003587.
- Sindilariu, P.D. (2007) Reduction in effluent nutrient loads from flow-through facilities for trout production: A review. *Aquaculture Research* 38, 1005-1036
- Soto, D. (2009) Integrated mariculture. A global review. FAO Fisheries and Aquaculture Technical Paper 529. Food and Agriculture Organization of the United Nations, Rome, p. 183.
- Tacon, A.G.J. (1998) Feeding tomorrow's fish. *Infofish international*, 11-33
- Tacon, A.G.J., De Silva, S.S. (1997) Feed preparation and feed management strategies within semi-intensive fish farming systems in the tropics. *Aquaculture* 151, 379-404
- Tallec, G., Garnier, J., Gossailles, M. (2006) Nitrogen removal in a wastewater treatment plant through biofilters: Nitrous oxide emissions during nitrification and denitrification. *Bioprocess and Biosystems Engineering* 29, 323-333
- Tansel, B., Jolis, D., Ho, C.F.H. (2006) Gaseous emissions from wastewater facilities. *Water Environment Research* 78, 1469-1485
- Thomson, A.J., Giannopoulos, G., Pretty, J., Baggs, E.M., Richardson, D.J. (2012) Biological sources and sinks of nitrous oxide and strategies to mitigate emissions. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367, 1157-1168
- Troell, M. (2009) Integrated marine and brackishwater aquaculture in tropical regions: research, implementation and prospects. In: Soto, D. (Ed.), *Integrated mariculture: A global review*. FAO Fisheries and Aquaculture Technical Paper, Rome, 47-131
- Van Drecht, G., Bouwman, A.F., Knoop, J.M., Beusen, A.H.W., Meinardi, C.R. (2003) Global modeling of the fate of nitrogen from point and nonpoint sources in soils, groundwater and surface water. *Global Biogeochemical Cycles* 17, 1115, doi:10.1029/2003GB002060.
- Wakida, F.T., Lerner, D.N. (2005) Non agricultural sources of groundwater nitrate: a review and a case study. *Water Resources* 39, 3-16
- Williams, J., Crutzen, P.J. (2010) Nitrous oxide from aquaculture. *Nature Geoscience* 3, 143.
- Zamora, L.M., Oschlies, A., Bange, H.W., Huebert, K.B., Craig, J.D., Kock, A., Löscher, C.R. (2012) Nitrous oxide dynamics in low oxygen regions of the Pacific: Insights from the MEMENTO database. *Biogeosciences* 9, 5007-5022
- Zhang, J., Gilbert, D., Gooday, A.J., Levin, L., Naqvi, S.W.A., Middelburg, J.J., Scranton, M., Ekau, W., Peña, A., Dewitte, B., Oguz, T., Monteiro, P.M.S., Urban, E., Rabalais, N.N., Ittekkot, V., Kemp, W.M., Ulloa, O., Elmgren, R., Escobar-Briones, E., Van der Plas, A.K. (2010) Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. *Biogeosciences* 7, 1443-1467

Chapter 8

- Allen, C., Clouth, S. (2012). *A Guidebook to the Green Economy*. United Nations Division for Sustainable Development (UNDESA), New York
- Birch M.B.L., Gramig B.M., Moomaw W.R., Doering III O.C., Reeling C.J. (2011) Why metrics matter: Evaluating policy choices for reactive nitrogen in the Chesapeake Bay water-shed. *Environ. Sci. Technol.* 45, 168-174
- Bleeker, A., Hicks, W.K., Dentener, F., Galloway, J., Erisman J.W. (2011) N deposition as a threat to the World's protected areas under the Convention on Biological Diversity. *Environmental Pollution* 159, 2280-2288
- Brink, C., van Grinsven, H., Jacobsen, B.H., Rabl, A., Gren, I.M., Holland, M., Klimont, Z., Hicks, K., Brouwer R., Dickens R., Willems J., Termansen M., Velthof G., Alkemade R., van Oorschot M. Webb J. (2011) Costs and benefits of nitrogen in the environment. In: *The European Nitrogen Assessment*. Sutton, M.A., Howard, C.M., Erisman, J.W.,

- Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H.J.M., Grizzetti B. (Eds.), pp 513-540. Cambridge University Press.
- Compton J.E., Harrison J.A., Dennis R.L., Greaver T.L., Hill B.H., Jordan S.J., Walker H., Campbell H.V. (2011) Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making. *Ecology Letters* 14, 804-15
- Davidson, E. A. (2009) The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience* 2, 659-662
- Davidson, E. A. (2012). Representative concentration pathways and mitigation scenarios for nitrous oxide. *Environmental Research Letters* 7, 024005. doi:10.1088/1748-9326/7/2/024005.
- DECC (2011) Government Response to the Consultation on the UK unilateral opt-in of Nitrous Oxide emissions from nitric acid production into Phase II of the EU Emissions Trading System. UK Department Energy and Climate Change, London. www.gov.uk/government/uploads/system/uploads/attachment_data/file/43239/1668-govt-resp-cons-n20-optin.pdf
- Dobermann, A. (2007) Nutrient use efficiency - measurement and management. Proceedings of the IFA Workshop on Fertilizer Best Management Practices. Brussels, Belgium. (March 7-9, 2007). International Fertilizer Industry Association, Paris.
- Gu B., Ge Y., Ren Y., Xu B., Luo W., Jiang H., Gu B., Chang J. (2012) Atmospheric reactive nitrogen in China: sources, recent trends and damage costs. *Environ. Science & Technology* 46, 9420-9427
- IEA (International Energy Agency). (2013). CO₂ emissions from fuel combustion. IEA Statistics. International Energy Agency. <http://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2013.pdf>
- IFDC (2012) Fertilizer Deep Placement (FDP), International Fertilizer Development Center [http://www.ifdc.org/Technologies/Fertilizer/Fertilizer_Deep_Placement_\(UDP\)](http://www.ifdc.org/Technologies/Fertilizer/Fertilizer_Deep_Placement_(UDP))
- Kanter D., Mauzerall D.L., Ravishankara A.R., Daniel J.S., Portmann R.W., Grabel P.M., Moomaw W.R. Galloway J.N. (2013) A post-Kyoto partner: Considering the stratospheric ozone regime as a tool to manage nitrous oxide. Proceedings of the National Academy of Sciences, 110(12), 4451-4457.
- Lamarque, J.F., Bond T.C., Eyring V., Granier C., Heil A., Klimont Z., Lee D., Liousse C., Mieville A., Owen B., Schultz M.G., Shindell D., Smith S.J., Stehfest E., Van Aardenne J., Cooper O.R., Kainuma M., Mahowald N., McConnell J.R., Naik V., Riah K., van Vuuren D.P. (2010) Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmos. Chem. Phys.* 10, 7017–7039, doi:10.5194/acp-10-7017-2010.
- Millar N., Robertson G.P., Grace P.R., Gehl R.J., Hoben J.P. (2010) Nitrogen fertilizer management for nitrous oxide (N₂O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture. *Mitigation and Adaptation Strategies for Global Change* 15, 185-204
- Nakicenovic, N., O. Davidson, G. Davis, A. Grübler, T. Kram, E. Lebre La Rovere, B. Metz, T. Morita, W. Pepper, H. Pitcher, A. Sankovski, P. Shukla, R. Swart, R. Watson, Z. Dadi (2000) Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press
- OECD (2011) Towards Green Growth. Paris: Organization for Economic Cooperation and Development.
- Oenema, O., Salomez, J., Branquinho, C., Budňáková, Černák P., Geupel, M., Johnse, P., Tompkins, C., Spranger, T., Erisman, J.W., Pallière, C., Maene, L., Alonso, R., Maas, R., Magid, J., Sutton, M.A., van Grinsven, H. (2011) Developing integrated approaches to nitrogen management. Chapter 23 In: *The European Nitrogen Assessment*. Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt P., van Grinsven H., Grizzetti B. (Eds.) pp 541-550. Cambridge University Press.
- Reay, D.S., Davidson, E.A., Smith P., Melillo J.M., Dentener, F. & Crutzen, P.J. (2012) Global agriculture and nitrous oxide emissions. *Nature Climate Change* Volume:2, Pages:410-416.
- Reay, D.S., Howard, C.M., Bleeker, A., Higgins, P., Smith, K., Westhoek, H., Rood, T., Theobald, M.R., Sanz Cobena, A., Rees, R.M., Moran, D., Reis, S. (2011) Societal choice and communicating the European nitrogen challenge. In: *The European Nitrogen Assessment*. Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.) Cambridge University Press, Cambridge.
- Savant N.K., Stangel P.J. (1990) Deep placement of urea supergranules in transplanted rice: Principles and practices. *Fertilizer Research* 25, 1-85
- Skiba U., Jone, S., Dragosis U., Drewer, J., Fowler D., Rees R., Pappa V., Cardenas L., Chadwick D., Yamulki. S. (2012). UK emissions of the greenhouse gas nitrous oxide. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367,1175-1185
- Snyder C.S., Bruulsema T.W. (2007) Nutrient use efficiency and effectiveness in North America: Indices of agronomic and environmental benefit. International Plant Nutrition Institute (IPNI), Norcross, Georgia, USA.
- Sutton M.A., Bleeker A., Howard C.M., Bekunda M., Grizzetti B., de Vries W., van Grinsven H.J.M., Abrol Y.P., Adhya T.K., Billen G., Davidson E.A, Datta A., Diaz R., Erisman J.W., Liu X.J., Oenema O., Palm C., Raghuram N., Reis S., Scholz R.W., Sims T., Westhoek H. & Zhang F.S., with contributions from Ayyappan S., Bouwman A.F., Bustamante M., Fowler D., Galloway J.N., Gavito M.E., Garnier J., Greenwood S., Hellums D.T., Holland M., Hoysall C., Jaramillo V.J., Klimont Z., Ometto J.P., Pathak H., Plocc F, Fichet V., Powlson D., Ramakrishna K., Roy A., Sanders K., Sharma C., Singh B., Singh U., Yan X.Y., Zhang Y. (2013a) Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative. 114 pp.
- Sutton M.A., Erisman J.W., Oenema O. (2007) Strategies for controlling nitrogen emissions from agriculture: Regulatory, voluntary and economic approaches. In: *Fertilizer Best Management Practices: General Principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations*. pp 245-259. International Fertilizer Industry Association, Paris. (ISBN 2-9523139-2-X).
- Sutton M.A., Howard C.M., Bleeker A., Datta A. (2013b) The global nutrient challenge: From science to public engagement. *Environmental Development* 6, 80-85
- Sutton, M.A., Skiba, U.M., van Grinsven, H., Oenema, O., Watson, C., Williams, J., Hellums, D., Maas, R., Gyldenkaerne, S., Pathak H., Winiwarter, W. (2014) Green Economy thinking and the control of nitrous oxide emissions. *Environmental Development* 9 (Jan 2014 issue), In press.
- UN (2012). The Future We Want. Rio+20 Outcome Document. <http://www.uncsd2012.org/thefuturewewant.html>
- UNECE (2012) Draft guidance document on national nitrogen budgets. Prepared by Expert Panel on Nitrogen Budgets, and submitted by the Co-chairs of the Task Force on Reactive Nitrogen; 31-03-2012, Executive Body of the Convention on Long-range Transboundary Air Pollution, Geneva.
- UNEP (2010) Green Economy Developing Countries Success Stories. United Nations Environment Program, Geneva.
- UNEP (2013a). The Emissions Gap 2013. United Nations Environment Program: Nairobi. <http://www.unep.org/pdf/UNEPemissionsGapReport2013.pdf>
- UNEP (2013b) Content of CDM/JI Pipeline: CERS”, UNEP RISØ Centre for Energy, Climate and Sustainable Development, <http://cdmpipeline.org/cers.htm#3>
- van Grinsven H.J.M., Holland M., Jacobsen B.H., Klimont Z., Sutton M.A., Willems W.J. (2013) Costs and benefits of nitrogen for Europe and implications for mitigation. *Environmental Science & Technology* 47, 3571-3579. dx.doi.org/10.1021/es303804g
- van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, W. Krey, J.F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, S.K. Rose (2011a). The representative concentration pathways: an overview. *Climatic Change* 109: 5-31
- WHO/FAO (2002) Joint WHO/FAO Expert Consultation on diet, nutrition and the prevention of chronic diseases, World Health Organization and Food and Agriculture Organization: Geneva.
- Winiwarter, W., Erisman, J.W., Galloway, J.N., Klimont, Z., Sutton M.A. (2013) Estimating environmentally relevant fixed nitrogen demand in the 21st century. *Climatic Change* 120:889-890
- Winiwarter, W., Höglund-Isaksson, L., Schöpp, W., Tohka, A., Wagner, F., Amann, M. (2010) Emission mitigation potentials and costs for non-CO₂ greenhouse gases in Annex-I countries according to the GAINS model. *Journal of Integrative Environmental Sciences*, 7, 235–243
- WMO/UNEP (2011) Scientific Assessment of Ozone Depletion: 2010. Global Ozone Research and Monitoring Project–Report No. 52, World Meteorological Organization / United Nations Environment Program.
- Zhang, W.F., Dou, Z.X., He, P., Ju, X.T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.L., Zhang, Y., Wu, L., Chen, X.P., Cassman, K.G., Zhang, F.S. (2013) New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *PNAS*. doi: 10.1073/pnas.1210447110.

www.unep.org

United Nations Environment Programme
P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +254 20 762 1234
Fax: +254 20 762 3927
e-mail: unep@unep.org
www.unep.org



ISBN: 978-92-807-3358-7
Job. No: DEW/1748/NA



9 789280 733587 >