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GLOBAL NITROUS OXIDE ASSESSMENT

CLIMATE &
CLEAN AIR
COALITION
TO REDUCE SHORT-LIVED
CLIMATE POLLUTANTS
a UNEP convened initiative

INMS

Required citation: United Nations Environment Programme and Food and Agriculture Organization. 2024. *Global Nitrous Oxide Assessment.* Nairobi. https://doi.org/10.59117/20.500.11822/46562

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ISBN: 978-92-807-4192-6
Job number: DTI/2679/NA
DOI: https://doi.org/10.59117/20.500.11822/46562

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Published by:

United Nations Environment Programme
and
the Food and Agriculture Organization of the United Nations

ACKNOWLEDGEMENTS

The Climate and Clean Air Coalition (CCAC), a United Nations Environment Programme (UNEP) convened initiative; the International Nitrogen Management System (INMS); and the Food and Agricultural Organization of the United Nations (FAO) would like to thank the report's Co-Chairs; High Level Panel members; the coordinating lead, lead and contributing authors; the expert reviewers and the project coordination team for their contribution to the development of this report.

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This Assessment was produced jointly in collaboration with the leadership of the forthcoming International Nitrogen Assessment (INA).

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Special Thanks

The co-chairs are grateful for the incredible support from Kevin Hicks, Scarlett Quinn-Savory, and Nathan Borgford-Parnell. Their continued help and critical inputs at crucial times enabled the completion of this Assessment. The co-chairs are also grateful to the coordinating lead, lead and contributing authors who took on carrying out modelling and analyses in a very short time. The co-chairs especially thank Eric Davidson, Drew Shindell and Rona Thompson for their many inputs and contributions. Mark Sutton’s critical input at specific junctures is greatly appreciated.

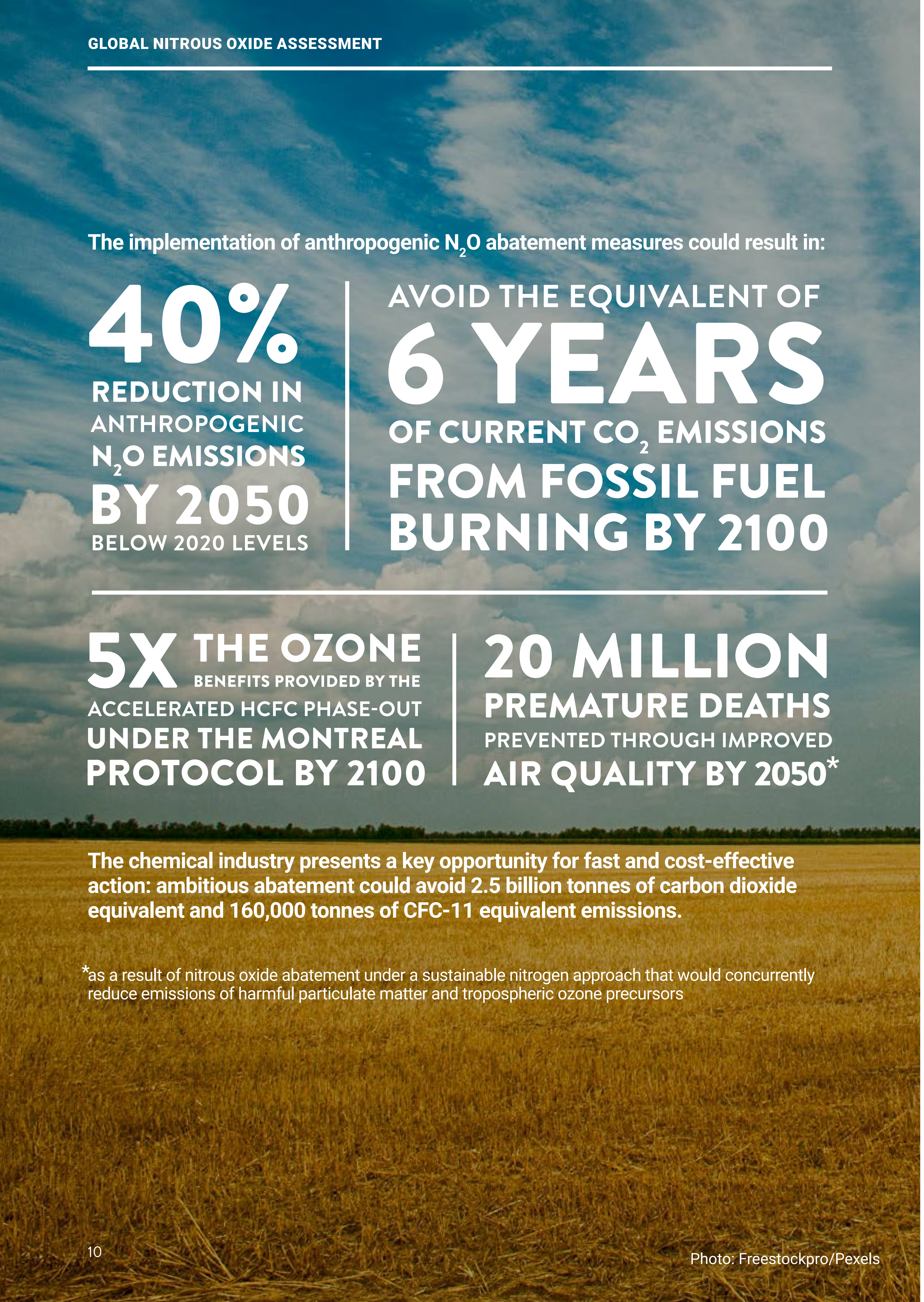
The production of this Assessment would not have been possible without close collaboration with the forthcoming *International Nitrogen Assessment* (INA) and INMS. INMS is supported by the Global Environment Facility. The INA is due to be launched in 2025.

Thanks are also extended to Ann Foo, for her contribution to Figure 5.8, and the Institute for Governance & Sustainable Development (IGSD), who assisted the coordination of this Assessment.

The Global Nitrous Oxide Assessment was funded and supported by the CCAC Trust Fund, ClimateWorks Foundation and the Grantham Foundation.

CONTENTS

Supplementary Information is available online at: www.ccacoalition.org/resources/global-nitrous-oxide-assessment



The implementation of anthropogenic N_2O abatement measures could result in:

40%
REDUCTION IN ANTHROPOGENIC N_2O EMISSIONS BY 2050
BELOW 2020 LEVELS

AVOID THE EQUIVALENT OF
6 YEARS
OF CURRENT CO_2 EMISSIONS FROM FOSSIL FUEL BURNING BY 2100

5X THE OZONE
BENEFITS PROVIDED BY THE ACCELERATED HCFC PHASE-OUT UNDER THE MONTREAL PROTOCOL BY 2100

20 MILLION PREMATURE DEATHS
PREVENTED THROUGH IMPROVED AIR QUALITY BY 2050*

The chemical industry presents a key opportunity for fast and cost-effective action: ambitious abatement could avoid 2.5 billion tonnes of carbon dioxide equivalent and 160,000 tonnes of CFC-11 equivalent emissions.

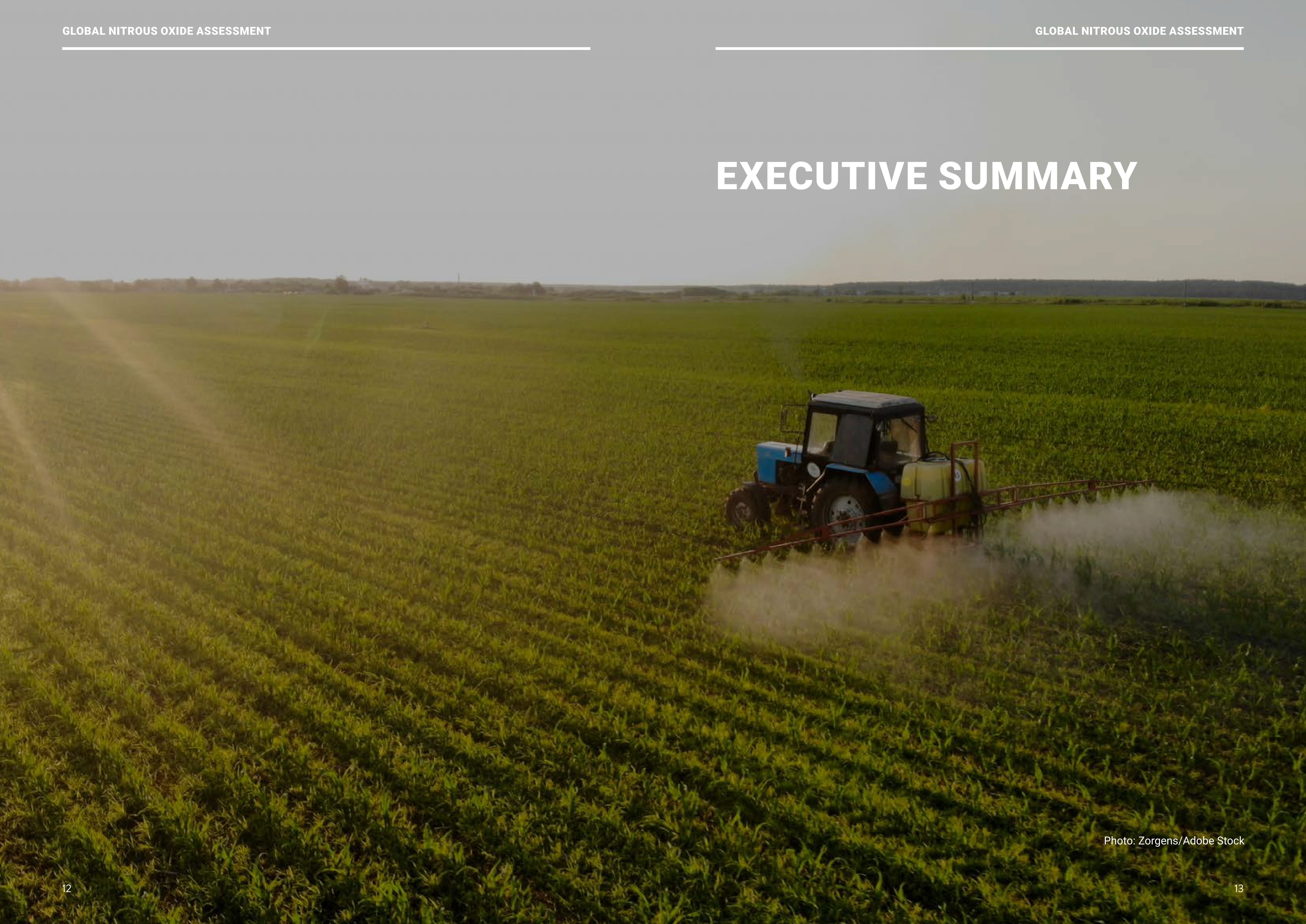
*as a result of nitrous oxide abatement under a sustainable nitrogen approach that would concurrently reduce emissions of harmful particulate matter and tropospheric ozone precursors

Photo: Freestockpro/Pexels

AUDIENCE AND FOCUS

This *Global Nitrous Oxide Assessment* is the first international report focused solely on nitrous oxide in more than a decade. It sheds new light on a super pollutant and is intended as a resource for policymakers, civil society, the private sector, the scientific community and others. An in-depth analysis of the nitrogen challenge (of which nitrous oxide is a part) will be outlined in the forthcoming *International Nitrogen Assessment* and a roadmap for action in the agri-food sector is the focus of a forthcoming CCAC assessment. The *Global Nitrous Oxide Assessment* is a combination of new modelling, using state-of-the-art Earth system, atmospheric and health impact models to quantify the effects of nitrous oxide on climate, air quality and ozone. It also synthesises the most recent peer-reviewed literature on nitrous oxide budgets, scenarios and abatement options. The findings of this Assessment have been peer reviewed by more than 40 external reviewers.

Photo: Tawanboonnak/Adobe Stock



EXECUTIVE SUMMARY

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Nitrous oxide, considered to be a super pollutant, is the third most important greenhouse gas and the most significant ozone-layer depleting substance emitted today. Its human-induced emissions, which primarily originate from the agricultural use of synthetic fertilisers and manure, are increasing faster than previously projected. This Assessment identifies abatement measures available today that could reduce these emissions by more than 40 per cent below current levels. Transformations in food production and societal systems could lead to even deeper reductions.

Nitrous oxide is part of the nitrogen cycle – nitrogen is essential to all life on Earth and the global food system. The abatement of its anthropogenic emissions must be grounded in a sustainable nitrogen management approach which would also reduce the loss of other nitrogen compounds to the environment. Ambitious action using this approach could move the world closer to meeting its 1.5° Celsius temperature goal, protect the stratospheric ozone layer, and improve air and water quality, while protecting food security, ecosystems and human health. This approach is an important part of a super pollutant multi-benefit strategy, which, alongside efforts to achieve net zero carbon dioxide emissions by mid-century, is necessary to put the world on a sustainable path to meeting long-term climate goals.

OPPORTUNITY

Nitrous oxide is a long-lived greenhouse gas approximately 270 times more powerful than carbon dioxide per tonne of emission at warming the Earth. Its anthropogenic emissions are responsible for approximately 10 per cent (around 0.1° Celsius) of net global warming to date since the industrial revolution. It is also an ozone-layer depleting substance. Although nitrous oxide is not controlled under the Montreal Protocol, its current anthropogenic emissions are a larger threat to the ozone layer than any chemical controlled under this protocol. Ambitious action to reduce nitrous oxide emissions could move the world closer to meeting a wide range of global climate, ozone and other environmental and human health goals.

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CLIMATE BENEFITS

- If nitrous oxide emissions continue to increase at their current rate, there is no plausible pathway to limiting global warming to 1.5° Celsius in the context of sustainable development, as defined in the Paris Agreement. (Section 4.1.2)

- Even keeping current nitrous oxide emissions constant would constrain society's capacity to limit global warming to 1.5° Celsius and require much greater and costlier reductions of carbon dioxide and methane emissions.(Section 4.1.2)

- Ambitious nitrous oxide abatement could avoid the equivalent of up to 235 billion tonnes of carbon dioxide emissions by 2100, which is approximately 6 years of current carbon dioxide emissions from fossil fuel burning. (Section 4.1.2)

- A sustainable nitrogen management approach to agricultural nitrous oxide emissions could also significantly reduce emissions of short-lived nitrogen compounds – other nitrogen oxides and ammonia – which would rapidly improve air quality but cause additional near-term warming primarily due to the reduced cooling effect of aerosols. Due to nitrous oxide's long lifetime, the net effect of a sustainable nitrogen management approach would reduce warming in the longer term. This is well justified by the health benefits of improved air quality. By contrast, reductions in industrial nitrous oxide emissions provide climate benefits across all time scales. (Section 4.1.2)

OZONE LAYER PROTECTION

- Nitrous oxide is currently the most significant ozone-layer depleting substance being emitted to the atmosphere. The destructive capacity of today's nitrous oxide emissions approximately equals the sum of all other current ozone-depleting substance emissions.

- Through 2050, ambitious nitrous oxide abatement could provide roughly the same ozone benefits as the 2007 Montreal Protocol agreement to accelerate the phase-out of hydrochlorofluorocarbons. Through 2100, the benefits could accumulate to more than five times those of the accelerated phase out. (Sections 4.2.1, 4.2.3)

- Ambitious nitrous oxide abatement could avoid a 0.2–0.8 per cent increase in cataract cases and a 2-10 per cent increase in skin cancers by 2080-2090, depending on latitude. (Section 4.2.5)

- The lowest levels of ozone this century and beyond are expected to occur if nitrous oxide emissions continue unabated and carbon dioxide and methane are abated consistent with climate goals. In such a future, by the end of the century much of the world's population could be exposed to ultraviolet levels larger than peak ozone depletion in 1995-2005. (Sections 4.2.4)

Photo: Tom Fisk/Pexels

SAVING LIVES BY IMPROVING AIR QUALITY, PROTECTING FOOD SECURITY AND ALLEVIATING OTHER ENVIRONMENTAL IMPACTS

- Abatement of nitrous oxide emissions under a sustainable nitrogen management approach would significantly improve air quality through the concurrent abatement of ammonia and nitrogen oxide emissions that form harmful fine particulates and ground-level ozone. This would have multiple health benefits, especially for the most vulnerable in society, ultimately avoiding approximately 20 million premature deaths globally by 2050, of which roughly 4 million would be saved in the next decade. (Section 4.1.3)

- A sustainable nitrogen management approach would deliver significant additional benefits for water quality, soil health and the structure and functioning of ecosystems. Reducing nitrogen run-off would, for example, lower the risk of eutrophying water bodies and contaminating drinking water supplies, while reducing such associated human health impacts as decreasing the risk of colon cancer. These impacts are further discussed in the forthcoming *International Nitrogen Assessment*.

- Nitrous oxide abatement measures could be implemented while simultaneously meeting future food demand, consistent with existing food security goals. Achieving this will require significant efforts to increase the efficiency of agricultural nitrogen use and reduce excessive nitrogen application in many parts of the world. (Section 4.1.4)

NITROUS OXIDE: HOW FAST ARE EMISSIONS INCREASING AND FROM WHERE DO THEY COME?

While nitrous oxide emissions have both natural and anthropogenic sources, this Assessment focuses on the abatement of anthropogenic ones. These anthropogenic emissions have increased globally by 40 per cent since 1980, with approximately 75 per cent originating from the agricultural use of synthetic fertilisers and manure. This Assessment projects that, without abatement, global anthropogenic nitrous oxide emissions will increase by approximately 30 per cent over 2020 levels by 2050. (Sections 2.1, 2.2, 3.2.1; Figure 3.1)

- Anthropogenic nitrous oxide emissions have grown steadily since the pre-industrial era and have accelerated since the Green Revolution. Between 1980 and 2022, atmospheric concentrations increased from 301 to 336 parts per billion. Agriculture is currently the source of 75 per cent of those emissions, of which approximately 90 per cent comes from the use of synthetic fertilisers and manure on agricultural soils and 10 per cent from manure management. (Sections 2.1, 2.2)

- Industrial sources account for approximately 5 per cent of current anthropogenic nitrous oxide emissions. The dominant sources are the production of adipic acid, primarily used in synthetic fibres and foam, and nitric acid, mainly used in the manufacture of fertilisers, munitions and adipic acid. (Section 2.2)

- The remaining 20 per cent of anthropogenic nitrous oxide emissions come from fossil fuel combustion, wastewater treatment, aquaculture, biomass burning, and other sources. (Section 2.2)


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HOW TO REDUCE NITROUS OXIDE EMISSIONS

A variety of technologies and practices to reduce anthropogenic nitrous oxide emissions exist across all major sectors with a range of costs.

- This Assessment identifies currently available abatement measures that could reduce global anthropogenic nitrous oxide emissions by more than 40 per cent below current levels. This Assessment evaluates the impacts by 2050 of their implementation. (Section 3.2)

- Industrial emissions provide an opportunity for rapid nitrous oxide abatement. There are a number of cost-effective technologies that can effectively eliminate industrial nitrous oxide emissions and do not require significant changes to existing production processes. Ambitious abatement in these sectors alone could reduce emissions by approximately 2.5 billion tonnes of carbon dioxide equivalent and 160,000 tonnes of CFC-11 equivalent. (Sections 5.2, 6.2)

Photo: Peter Fazekas/Pexels

- The ozone-layer and climate benefits of nitrous oxide emissions abatement, as well as other ecosystem and health co-benefits, can only be delivered through ambitious action in agriculture. A sustainable nitrogen management approach that reduces nitrous oxide emissions could simultaneously enhance the resilience of food systems. (Section 3.2)

- There is an array of available technological, behavioural and structural measures that if implemented could reduce nitrous oxide emissions from agriculture and the broader food system by about 40 per cent below current levels emissions by 2050. These measures have been developed by farmers, the fertiliser industry and research institutions and are increasingly being implemented across the agri-food system. These include controlled-release fertilisers or formulations that inhibit nitrogen losses, the more selective use of fertilisers aided by soil-nitrogen testing, improved manure management, and behavioural changes such as lowering the consumption of animal protein in some populations. (Sections 3.2, 5.3, 5.4)

- There are a number of regulatory, economic, social and cultural barriers to abating agricultural nitrous oxide emissions that need to be addressed to ensure lasting farmer adoption of abatement practices and technologies, and enable more transformative societal changes. (Sections 5.2, 5.3)

- Agricultural nitrous oxide emissions vary enormously around the world as a result of large differences in synthetic fertiliser and manure use. Some regions do not use enough fertiliser, legumes or other nitrogen fixing crops, or manure to guarantee food security, while regions with high application rates, above crop needs, offer the greatest potential for total nitrous oxide abatement. (Sections 5.3, 5.4)

- Opportunities to reduce other sources of nitrous oxide emissions include improving wastewater treatment, while also reducing biomass burning and fossil fuel combustion. (Sections 3.2, 5.6)

Table ES.1 Overview of example nitrogen abatement measures by sector that could significantly reduce nitrous oxide emissions. (Section 3; Table 3.4)

AGRICULTURAL SECTOR	**Nitrogen testing:** Soil and plant nitrogen testing
	Nitrogen application: Split application using controlled-release fertilisers; urease and nitrification inhibitors; reduced application rates; and increased manure recycling
	Crop management: Integrating nitrogen-fixing crops in rotations; reduced tillage; and the use of cover crops
	Livestock diets: Optimising protein intake
	Grazing: Rotational grazing
	Manure storage/process: Solid/slurry separation; storage under dry conditions and rapid drying; anaerobic digestion.
	Drainage control: Buffer strips
	Planning: Integration of crop and livestock production
CHEMICAL SECTOR	**Adipic acid production:** Catalytic reduction and thermal destruction
	Nitric acid production: Catalytic reduction and thermal destruction
WASTE SECTOR	**Wastewater:** Process optimisation to increase the N_2/N_2O ratio

AVOID TRADE-OFFS

Several emerging decarbonisation measures could result in increased nitrous oxide emissions.

- There is a considerable risk that increasing the use of ammonia as a fuel for marine shipping and biofuels derived from fertilised crops could produce significant nitrous oxide emissions, partially or completely offsetting their intended climate benefits. For example, recent studies suggest that nitrous oxide emissions from the use of ammonia as a shipping fuel could, if not managed properly, exceed agricultural nitrous oxide emissions. (Section 6.3.3)
- The trade-offs between carbon dioxide, methane and nitrous oxide abatement in all sectors need to be better understood so that technologies can be improved and policies developed to manage the risks. (Section 6.3.3)

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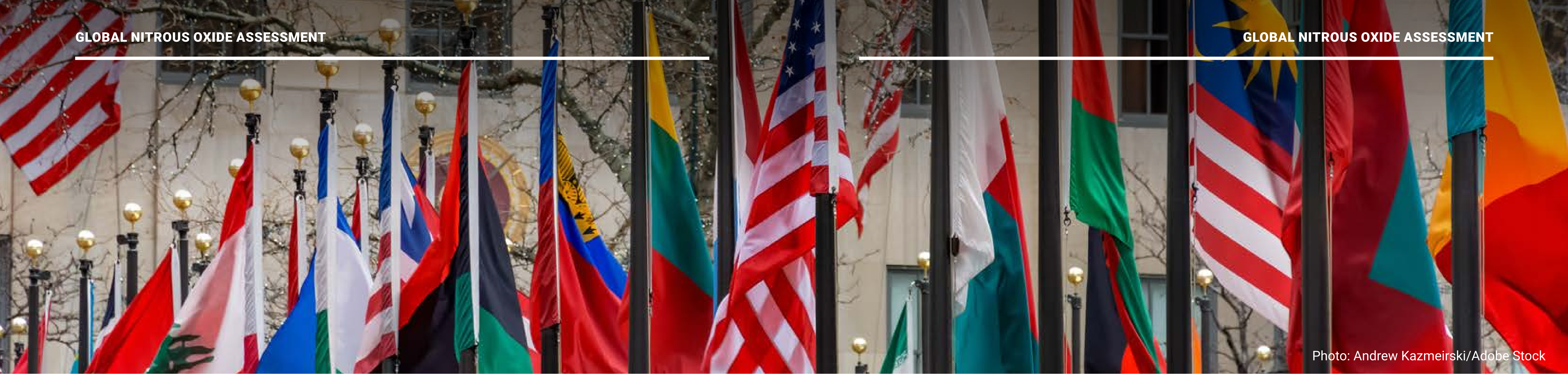

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MULTILATERAL OPTIONS FOR ACTION ON NITROUS OXIDE

Nitrous oxide's impacts on the ozone layer and climate, coupled with its close links to other nitrogen compounds, means that it falls under the remits of several multilateral environmental agreements, including the Paris Climate Agreement and the Vienna Convention for the Protection of the Ozone Layer. (Section 6.4)

Moreover, an integrated approach through sustainable nitrogen management including ambitious nitrous oxide abatement would enable associated reductions in other nitrogen compounds and contribute to achieving several other international targets. These include:

- Target 7 of the Global Biodiversity Framework: at least halving nutrient losses to the environment by 2030;
- The Gothenburg Protocol targets on ammonia and nitrogen oxides under the Convention on Long Range Transboundary Air Pollution;
- Number of the Sustainable Development Goals, notably including:

  Goal 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture;

  Goal 6: Ensure availability and sustainable management of water and sanitation for all;

  Goal 12: Ensure sustainable consumption and production patterns;

  Goal 13: Take urgent action to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy.

Ultimately, the successful implementation of any multilateral effort to reduce nitrous oxide or nitrogen losses more broadly will require concerted action at national and sub-national scales.

CHAPTER 1:

INTRODUCTION TO THE ASSESSMENT FROM THE CO-CHAIRS

Co-Chairs of the Global Nitrous Oxide Assessment:
David R. Kanter and A.R. Ravishankara

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Anthropogenic nitrous oxide, an unintended byproduct of many human activities, is a significant threat to climate and the ozone layer. Its dual properties as a greenhouse gas and an ozone-layer depleting substance have been known to the scientific community for decades.

And yet nitrous oxide has been consistently overlooked by the international climate and ozone conventions. While the Vienna Convention to Protect the Ozone Layer has long listed it as a substance that can potentially modify the chemical and physical properties of the ozone layer, it is not currently a controlled substance under the Montreal Protocol. And though it is listed as one of the greenhouse gases in the basket of the United Nations Framework Convention on Climate Change (UNFCCC), there has been minimal action taken in any nationally determined contributions (NDCs).

This new *Global Nitrous Oxide Assessment* – a joint effort by the Climate and Clean Air Coalition (CCAC), a United Nations Environment Programme (UNEP) convened initiative, the International Nitrogen Management System (INMS) and the Food and Agricultural Organization of the United Nations (FAO) – highlights the important opportunities and benefits of ambitious nitrous oxide abatement, as well as the serious risks of continued inaction.

The CCAC is an initiative of more than 160 partner countries and organisations to reduce short-lived climate pollutants (SLCPs), such as methane and hydrofluorocarbons. Nitrous oxide is not short lived, it has a lifetime of approximately 120 years, and is a powerful greenhouse gas, approximately 270 times more powerful than carbon dioxide on a molecule-for-molecule basis. Its abatement has important consequences for air pollution given that other nitrogen compounds co-emitted with it are key air pollutants. Consequently, the CCAC was tasked in March 2024 with rapidly developing the new *Global Nitrous Oxide Assessment* with a view to enabling more ambitious climate and ozone abatement efforts.

The *International Nitrogen Assessment* (INA) is a product of the Towards International Nitrogen Management System project and will be published in 2025. It examines all the components of the nitrogen cycle, including nitrous oxide, ammonia, nitrogen oxides, nitrate and other nitrogen compounds that can be lost to the environment. It looks across all major world regions, the environmental and human health impacts of nitrogen pollution, and the economic and political implications of more sustainable nitrogen management. It evaluates nitrogen's role in food security and sustainable development.

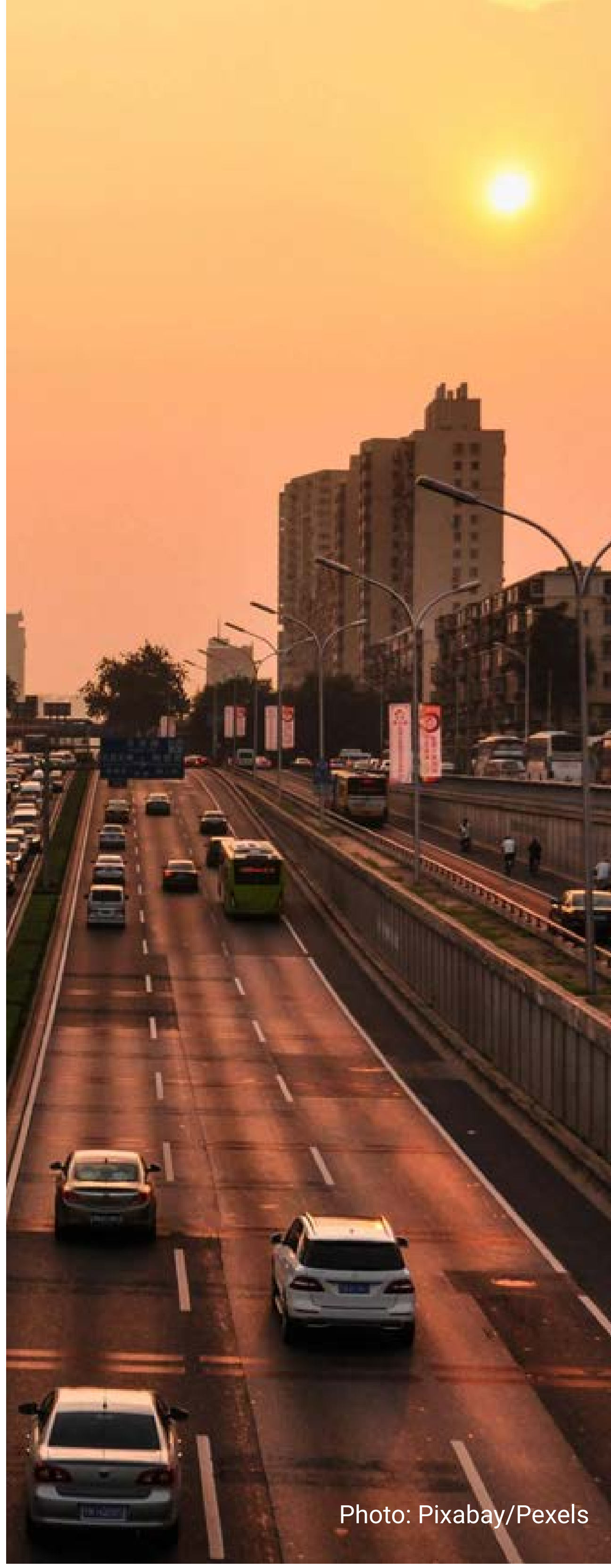
This Assessment supplements the INA with new modelling and analysis specific to nitrous oxide. It also applies several of its approaches, including the use of three nitrogen-specific scenarios and a sustainable nitrogen management approach to nitrous oxide abatement. Such an approach is critical as it increases the likelihood of generating significant co-benefits from the reductions of other nitrogen pollutants and minimises the risk of abatement action reducing nitrous oxide emissions while inadvertently increasing the loss of other nitrogen compounds. Readers interested in this *Global Nitrous Oxide Assessment* are strongly encouraged to engage with the forthcoming INA, given its much broader focus on the multiple, complex facets of the nitrogen challenge.

This *Global Nitrous Oxide Assessment* builds on the work done and synthesised for the latest Intergovernmental Panel on Climate Change (IPCC) assessments and the World Meteorological Organization (WMO)/UNEP ozone assessments, as well as the last global nitrous oxide assessment published by UNEP in 2013. That assessment included an examination of nitrous oxide's ozone and climate impacts, a sector-by-sector analysis of emissions budgets and abatement options, and an analysis of global policy options. This new Assessment presents an updated emissions budget, new projections of ozone, climate and air quality impacts under different scenarios, and the most recent evaluations of effectiveness and costs of abatement measures across all major sectors. It also introduces some of the potential risks of new decarbonisation technologies, including ammonia as a fuel for marine shipping, on nitrous oxide emissions. In short, it is a succinct, one-stop shop for stakeholders to find essential information on nitrous oxide.

Some vital new findings should be noted. Ambitious nitrous oxide abatement could avoid emissions equivalent to 235 billion tonnes of carbon dioxide by the end of century. Ambitious abatement could also generate ozone benefits equivalent to five times the accelerated hydrochlorofluorocarbon (HCFC) phase-out carried out under the Montreal Protocol. Nitrous oxide abatement's air quality benefits are a significant advantage with near-term benefits, avoiding 20 million premature deaths by 2050. The long lifetime of nitrous oxide means that the ozone and climate benefits of reducing emissions now will endure for decades and centuries. Finally, industrial emissions of nitrous oxide are a key low-hanging fruit for action with low abatement costs.

Over the past decade, the world has seen notable progress in international ozone and climate governance: the Paris Climate Agreement was signed in 2015, and the Global Methane Pledge was established in 2021; in 2016, the Montreal Protocol passed the Kigali Amendment to phase down the production and consumption of hydrofluorocarbons (HFCs). During this same period, there has been no meaningful action on nitrous oxide. Moreover, despite some of the progress made in policy pledges and new legislation, much more needs to be done to reduce greenhouse gas emissions in line with the Paris Climate Agreement's temperature goals and continue the recovery of the ozone layer. The central finding of this *Global Nitrous Oxide Assessment* is that if the international community is serious about meeting not just its international climate and ozone commitments but many of its sustainable development objectives – from clean air and water to improved health and food security – then ambitiously abating nitrous oxide is essential.

We sincerely hope this Assessment spurs more scientific and policy interest in nitrous oxide and nitrogen pollution. We hope it motivates all stakeholders – from policymakers through civil society to the private sector – to address nitrous oxide with the seriousness it deserves. Ambitious abatement would facilitate meeting many of our planetary commitments and increase the likelihood of a safe(r) planet for future generations.



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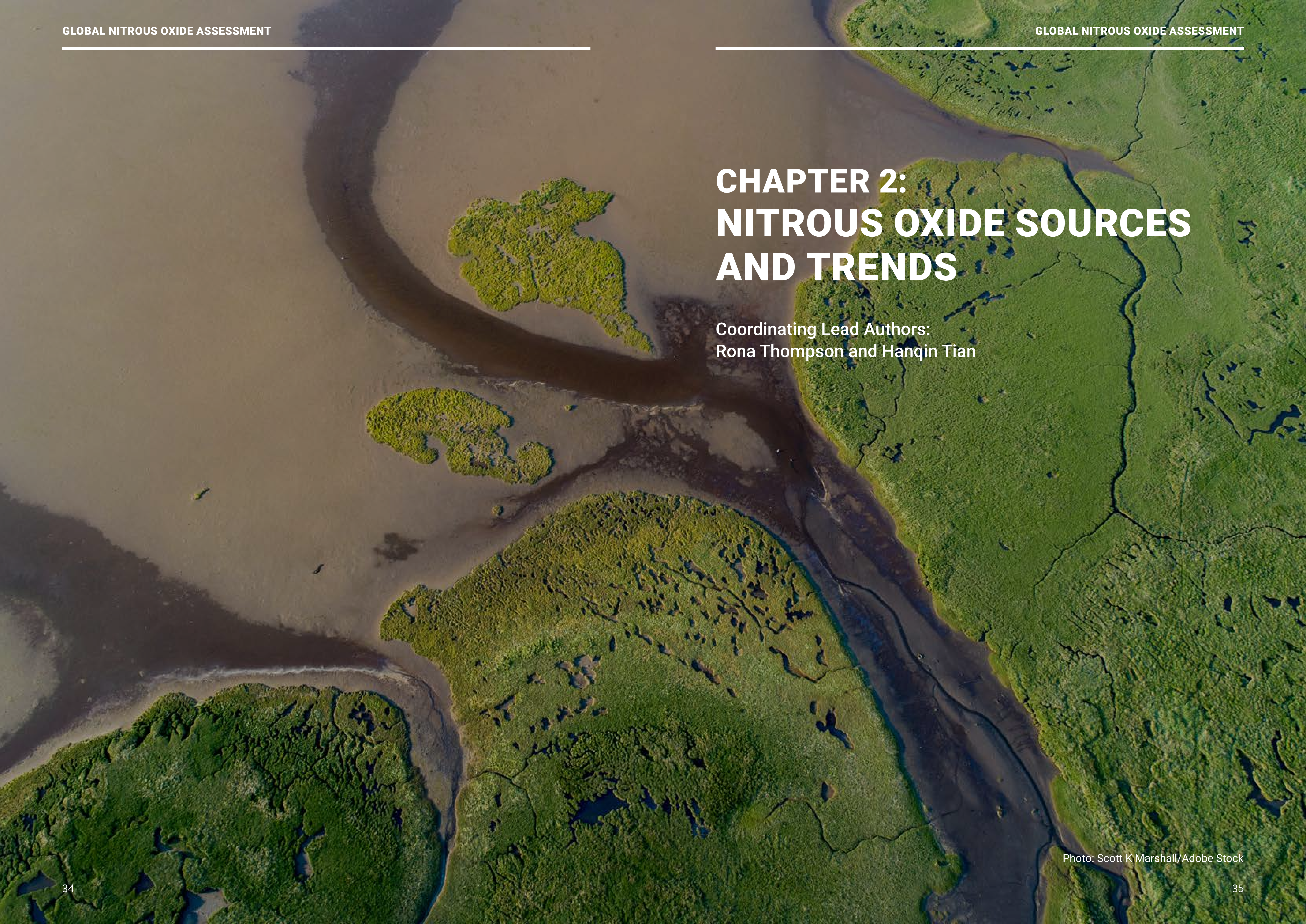

CHAPTER 2:
NITROUS OXIDE SOURCES AND TRENDS

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Rona Thompson and Hanqin Tian

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KEY MESSAGES

1. Atmospheric abundance of nitrous oxide has increased by more than 20 per cent since the pre-industrial era due to human activities.

2. Atmospheric abundance of nitrous oxide is increasing at an accelerating rate. The mean annual growth rate over the past five years (2017–2021) was 1.2 parts per billion a year and was nearly twice that of the early 2000s (2000–2004).

3. The increase in nitrous oxide abundance is primarily being driven by globally increasing emissions from agriculture.

4. Nitrous oxide's current contribution to warming is about 0.1° Celsius (C), and it is growing. Because it has a long atmospheric lifetime (around 120 years), its warming effect accumulates and will last a long time.

5. Nitrous oxide is currently the most significant ozone-depleting substance emitted and poses a serious threat to stratospheric zone.

2.1 INTRODUCTION

Nitrous oxide levels in the atmosphere have risen from between 270 and 280 parts per billion in pre-industrial times to more than 336 parts per billion in 2024.

Nitrous oxide (N_2O) levels in the atmosphere have risen from between 270 and 280 parts per billion (ppb) in pre-industrial times (Machida *et al.* 1995) to more that 336 ppb in 2024 (NOAA GML; Lan *et al*. 2024) (Figure 2.1). The rate of increase has accelerated since 2000, and the mean annual growth rate over the past five years (2017–2021) was 1.2 parts per billion per year (ppb/yr) while the mean in 2000–2004 was 0.68 ppb/yr. Prior to the 1970s, when direct sampling of the atmosphere began, the record was based on measurements made on samples of air extracted from firn and ice cores. Since the late 1970s, nitrous oxide has been measured directly in the atmosphere, starting with approximately five sites distributed globally, to more than 100 sites today (Prinn *et al*. 1990; Lan *et al.* 2024) and is measured by two independent global networks[1] with very good agreement between them.

Based on atmospheric records and an estimate of its average lifetime in the atmosphere, the global total nitrous oxide source can be determined (Figure 2.2). Throughout at least the last two millennia and up to the industrial revolution, the amount of nitrous oxide in the atmosphere, and thus also emissions, changed little (MacFarling Meure *et al*. 2006; Rubino *et al*. 2019). For the pre-industrial period up to the mid-19th century, emissions were stable at around 17.4 megatonnes of nitrous oxide per year[2] (Mt N_2O/yr) as derived from atmospheric observations. This estimate is quite consistent with inventory-based estimates of around 18.2 Mt/yr (Syakila and Kroeze 2011). Pre-industrial nitrous oxide emissions were predominantly from natural sources, primarily due to microbial processes in tropical soils and in the coastal and open ocean, which according to Syakila and Kroeze amounted to around 17.4 Mt/yr. In addition, there was a small source, of 0.8 Mt/yr, from agriculture due to the production and use of animal manure as well as the planting of nitrogen (N) fixing crops, such as legumes. Overall, the pre-industrial source was balanced by the sink of nitrous oxide in the stratosphere and the atmospheric level was stable (Kroeze *et al*. 1999; Syakila and Kroeze 2011).

From the end of the 19th century and into the beginning of the 20th century, anthropogenic nitrous oxide emissions increased gradually, due largely to the expansion and intensification of agriculture (Syakila and Kroeze 2011). Following the development of the Haber-Bosch process in 1910 to produce ammonia (NH_3) on a large-scale, a key step in producing synthetic nitrogen fertilisers, nitrous oxide emissions grew more rapidly. The nitrous oxide emission rate increased further in the second half of the 20th century, largely as a result of the rising use of synthetic fertilisers, and total emissions reached approximately 28.3 Mt/yr in 2020 based on atmospheric observations (calculation made for this Assessment). This estimate is very consistent with modelling-based estimates for the same year of 29.1 Mt/yr (Tian *et al*. 2024). For 2010–2019, anthropogenic sources contributed 35 per cent to total global emissions, while natural sources contributed 65 per cent. Emissions from natural sources have changed only a little since pre-industrial times, and today amount to around 18.5 Mt/yr (Tian *et al* 2024). Anthropogenic emissions have increased approximately 10-fold and are almost exclusively responsible for the increase in atmospheric nitrous oxide.

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[1] Nitrous oxide is measured by the Global Monitoring Laboratory network of National Oceanic and Atmospheric Administration (NOAA) and by the Advanced Global Atmospheric Gases Experiment (AGAGE) network.

[2] In this Assessment, emissions are given as the mass of nitrogen oxide. However, in some scientific literature the emissions are given in mass of nitrogen. To convert the emissions from mass of nitrogen to mass of nitrogen oxide one needs to multiply by 44/28.

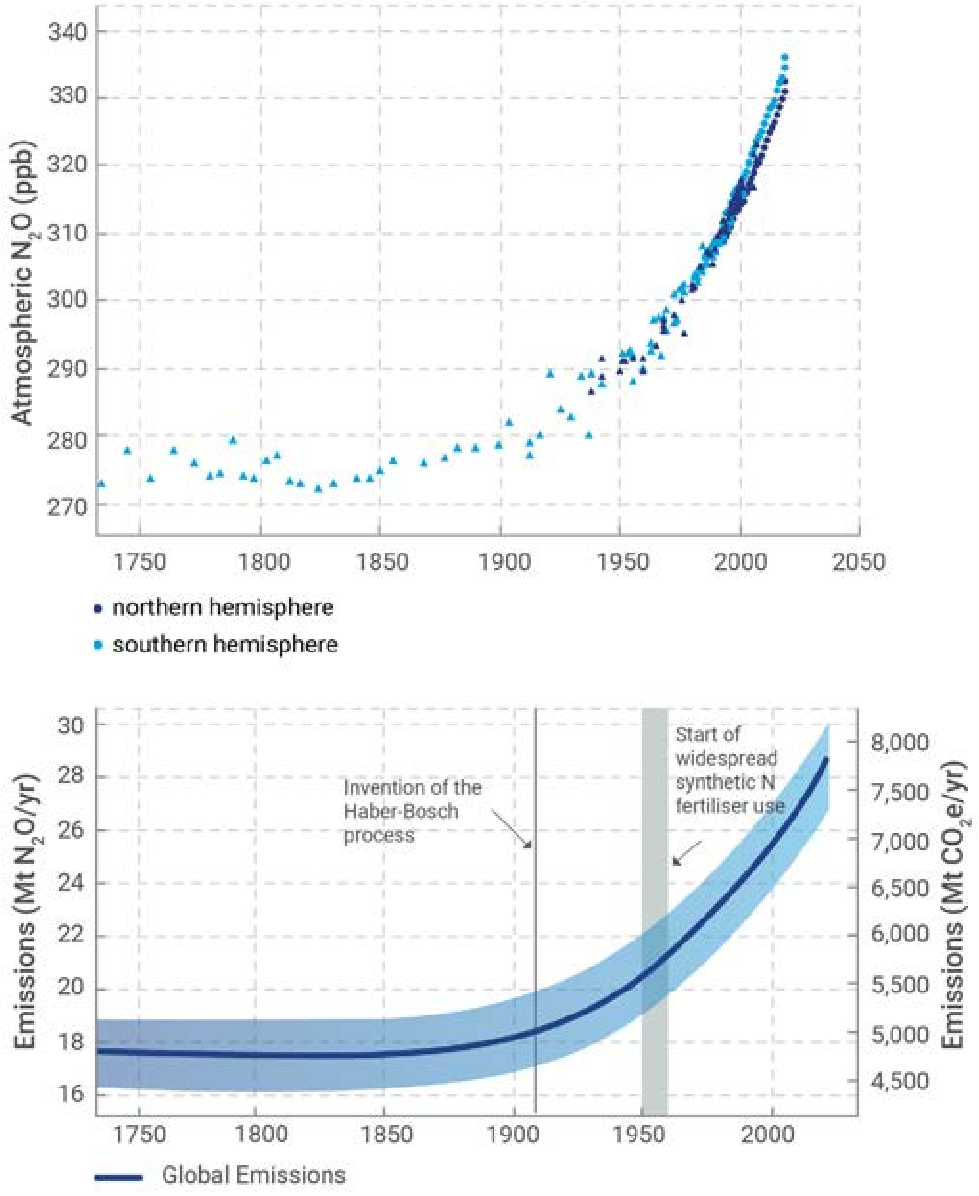

Figure 2.1 The top graph shows trends in atmospheric nitrous oxide levels derived from ice core or firn air (triangle) and ambient air (circle) measurements shown for the northern (dark blue) and southern (light blue) hemispheres, parts per billion by volume. The ambient air data are shown as annual means. The lower graph shows estimated global emissions and uncertainties based on the atmospheric levels assuming a constant lifetime of nitrous oxide of 116±9 years, nitrous oxide and carbon dioxide equivalent, megatonnes per year.

Sources: Machida *et al*. 1995; Ishijima *et al*. 2007; Park *et al*. 2012; Prokopiou *et al.* 2017 and 2018; Lan *et al.* 2024.

Increasing levels of nitrous oxide in the atmosphere have contributed to approximately 0.1°C (uncertainty range 0.07–0.14° C) of warming in 2019 relative to 1750, making nitrous oxide the third most important well-mixed anthropogenic greenhouse gas after carbon dioxide (CO_2) and methane (CH_4) (IPCC 2021). Although its contribution to warming is currently still modest compared to carbon dioxide and methane, nitrous oxide has a very high global warming potential (GWP) – it contributes 273 times more to radiative forcing on a per-mass basis compared to CO_2 over a time period of 100 years (IPCC 2021) – and has a lifetime of approximately 120 years so that the warming due to nitrous oxide is committed to for a long time.

In addition, nitrous oxide is a significant driver of stratospheric ozone (O_3) destruction as it is the primary source of nitrogen oxides (NO_x) – nitric oxide (NO) and nitrogen dioxide (NO_2) – in the stratosphere, which catalytically destroy ozone (Crutzen 1970; Johnston 1971; Ravishankara *et al.* 2009) (Figure 2.2). Nitrogen oxides are formed in the stratosphere through the destruction of nitrous oxide by photolysis and reaction with oxygen radicals). As emissions of chlorofluorocarbons (CFCs), such as trichlorofluoromethane (CFC-11), have decreased following the adoption of the Montreal Protocol on Substances that Deplete the Ozone Layer (UNEP 1987) in 1987, anthropogenic emissions of nitrous oxide have become the most significant emissions of ozone-depleting substances (ODS) and are likely to remain so throughout the 21st century (Revell *et al.* 2015). The increase of these emissions, which is still accelerating, has already been recognised by the Montreal Protocol's Scientific Assessment Panel as a serious threat to stratospheric ozone (WMO 2022).

Nitrous oxide emissions are also often associated with emissions of ammonia and nitrogen oxides to the atmosphere, which respectively leads to the formation of ammonium (NH_4^+) and nitrate (NO_3^-) aerosols in the atmosphere (Figure 2.3). These aerosols affect air quality and thus human health (de Vries 2021) but have a cooling effect on climate (Quaas *et al.* 2022). In addition, nitrogen oxides play a major role in the formation of tropospheric ozone, which further affects air quality, plant growth and human health, and is a greenhouse gas (Emberson 2020; Nguyen *et al*. 2022). On the other hand, nitrogen containing aerosols, when deposited on land where ecosystems are nitrogen-limited, can increase tree growth and thus enhance the uptake of carbon dioxide from the atmosphere, but at the same time may reduce biodiversity (de Vries 2021). The use of nitrogen fertilisers and manure in agriculture, a dominant source of anthropogenic nitrous oxide emissions, not only leads to nitrous oxide emissions but is also associated with increased concentrations of ammonium and nitrate in inland and coastal waters, due to nitrogen runoff and leaching, which impacts the quality of drinking water and aquatic biodiversity (de Vries 2021).

Photo: Nos/Adobe Stock

Nitrification and denitrification are the two key microbial processes controlling nitrous oxide production (Firestone and Davidson 1989; Butterbach-Bahl *et al*. 2013; Caranto *et al*. 2016; Kuypers *et al*. 2018), and occur in soils and inland waters, as well as in the coastal and open ocean, which together make the largest contribution to global nitrous oxide emissions. Abiotic processes also produce nitrous oxide but play a minor role. Biogenic nitrous oxide emissions from land are determined by multiple environmental factors, including soil moisture, temperature, oxygen status, acidity (pH), vegetation type, topography, atmospheric carbon dioxide concentration, and soil nitrogen and carbon (C) availability (Butterbach-Bahl *et al.* 2013; Tian *et al*. 2019; Yu *et al.* 2022). These environmental factors cause nitrous oxide emissions to vary strongly in space and time, making the up-scaling of field measurements to regional and global scales challenging. Ongoing environmental changes, such as ocean warming and associated changes in stratification and ice cover; decreasing pH (i.e., ocean acidification); loss of dissolved oxygen (O) (i.e., deoxygenation); and eutrophication, due to anthropogenic input of nutrients through rivers and atmospheric deposition of nitrogen aerosols, might significantly alter the production and consumption of nitrous oxide in the upper ocean. Ultimately, these changes may affect emissions to the atmosphere (Bange *et al.* 2019, 2022; Wilson *et al.* 2020), exerting a small but uncertain feedback on global warming in the long term (Battaglia and Joos 2018; Forster *et al.* 2021).

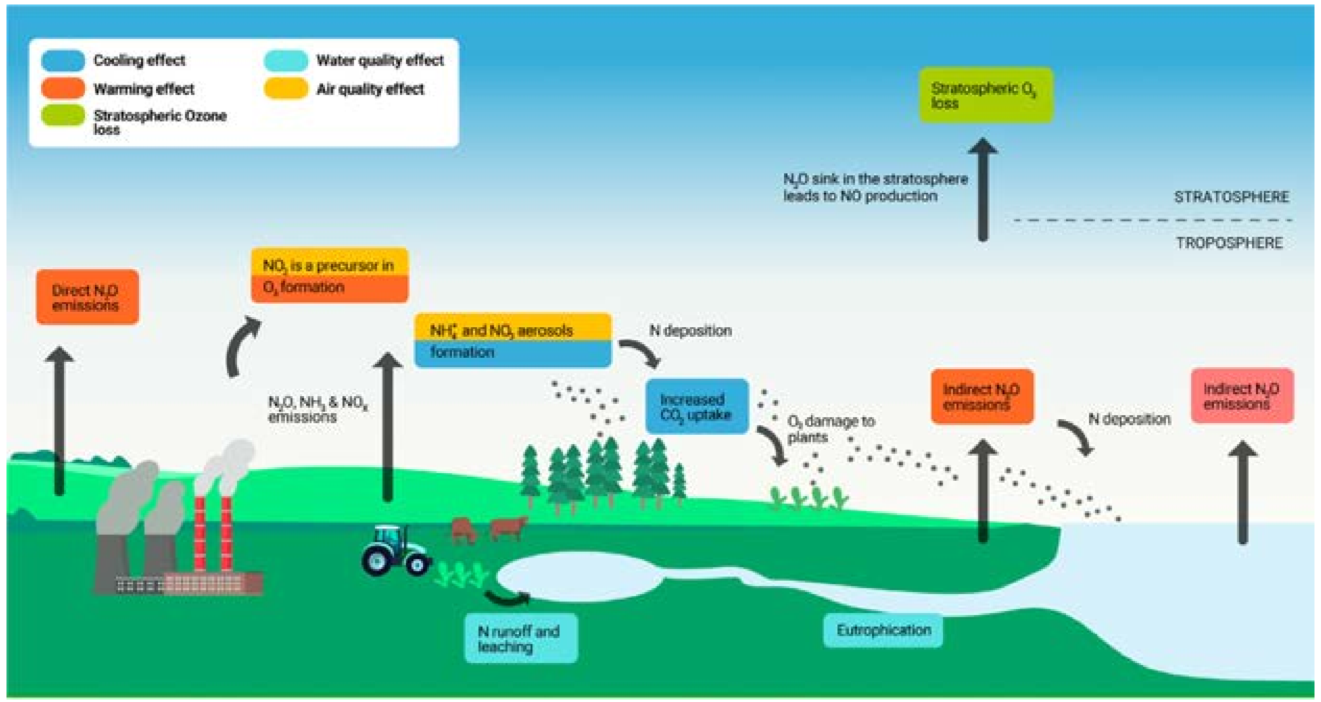

Figure 2.2 Impacts of anthropogenic nitrogen on nitrous oxide emissions, stratospheric ozone, as well as air and water quality.

BOX 2.1

NITROUS OXIDE EMISSION ESTIMATION TECHNIQUES

Nitrous oxide flux between the Earth's surface and the atmosphere is defined as positive when it is to the atmosphere (a source) and negative when it is to the surface (a sink). The term emission is used to describe a net positive flux to the atmosphere. Methods to estimate nitrous oxide emissions can be assigned to one of two overarching approaches: a bottom-up or top-down approach. More detail on emission estimation methods is given in the supplementary information (SI 2.1).

Bottom-up approaches entail estimating emissions at relatively small spatial scales, which are then integrated to give a regional or national estimate. The emissions can be estimated based on small-scale flux measurements that are scaled up using empirical models or inventories, which rely on the relationship of nitrous oxide flux to various environmental and/or land management parameters, such as soil temperature, soil moisture and nitrogen input (Butterbach-Bahl *et al.* 2013). Alternatively, small-scale flux measurements can be used to develop and/or calibrate process-based models, which parameterise nitrous oxide fluxes as a function of various environmental parameters (Tian *et al.* 2019), and these estimates can likewise be integrated to give regional or national estimates.

Top-down approaches use measurements of nitrous oxide in the atmosphere and a model of the relationship between changes in atmospheric concentration and fluxes, namely, an atmospheric chemistry transport model (Huang *et al.* 2008; Saikawa *et al.* 2014; Thompson *et al*. 2014). The spatial and temporal distribution of nitrous oxide in the atmosphere informs the magnitude and distribution of the fluxes. Top-down approaches can also give spatially and temporally resolved estimates of the fluxes, which again can be integrated to give regional or national estimates.

Both estimation approaches are associated with their own distinct sources of uncertainties. In general, bottom-up approaches are more accurate on small scales but their uncertainties increase with integration over space and time while top-down approaches are more accurate on larger scales and their uncertainties decrease with integration. The approaches can thus be said to be complementary (Tian *et al*. 2024). More detail on uncertainties in emissions estimation is given in the supplementary information (SI 2.1).

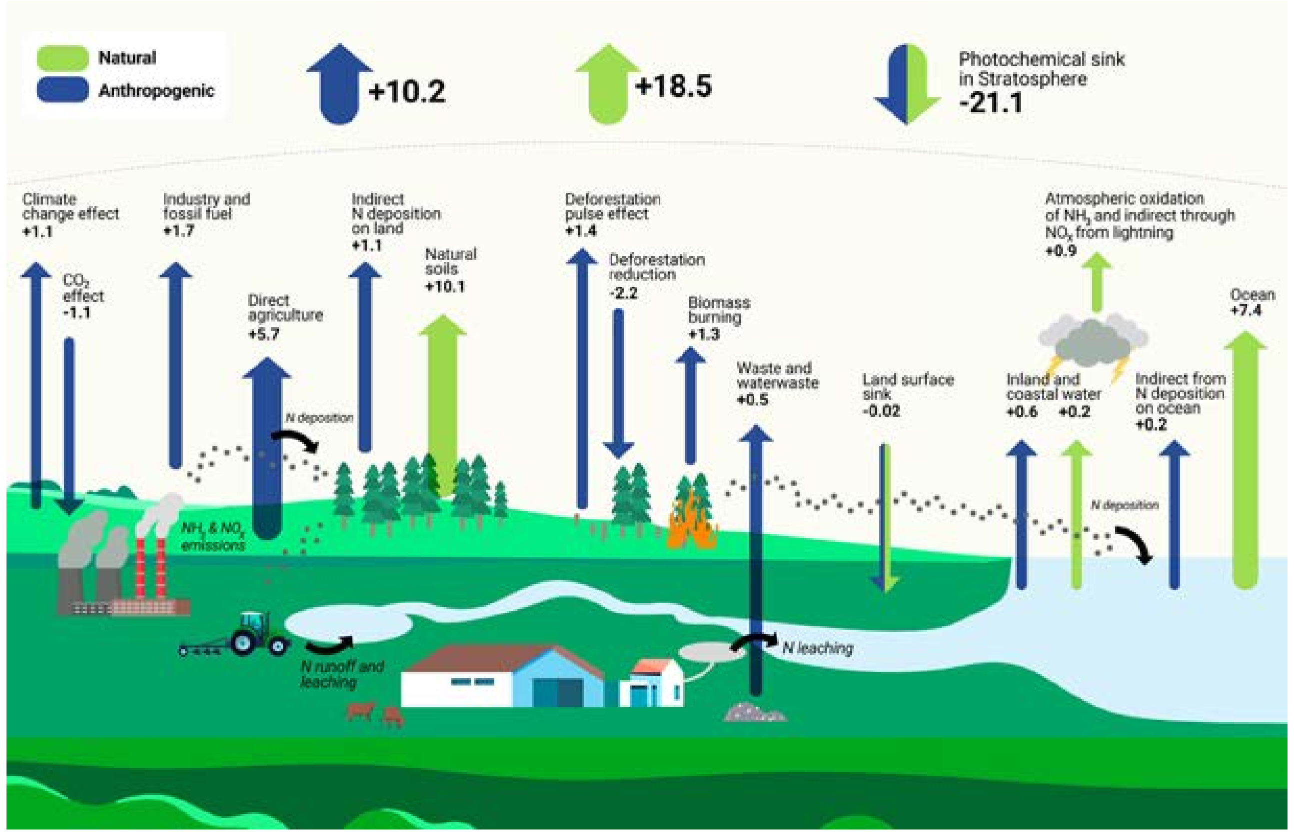

Figure 2.3 Nitrous oxide sources and sinks, megatonnes of nitrous oxide per year. Values shown are the mean for 2010–2019.
Source: Adapted from Tian *et al.* 2024.

2.2 ANTHROPOGENIC EMISSIONS BREAKDOWN

A recent assessment of the global nitrous oxide budget (Tian *et al*. 2024) estimated that global anthropogenic emissions were 10.2 megatonnes per year in the 2010s – 35 per cent of total nitrous oxide emissions in the period. In the past four decades, global anthropogenic emissions increased by 40 per cent from 7.6 Mt/yr in 1980 to 10.7 Mt/yr in 2020.

Anthropogenic emissions can be defined as direct and indirect emissions from different anthropogenic sources (Table 2.1; Figure 2.4). Table 2.1 presents recent estimates of anthropogenic emissions for five major categories and their associated sources, including mean, minimum and maximum values (Tian *et al*. 2024).


Photo: Industrieblick/Adobe Stock

2.2.1 Direct agricultural emissions

Direct agricultural emissions are defined as those from nitrogen additions in the agricultural sector. These consist of four components: i) direct soil emissions from the direct application of synthetic nitrogen fertiliser and manure on cropland; ii) manure left on pasture; iii) manure management; and iv) aquaculture. Process-based and empirical models estimate that direct agricultural emissions of nitrous oxide were 5.7 Mt/yr in the 2010s, 56 per cent of the total anthropogenic emissions in that period. The largest component of this source was from direct soil emissions, 3.1 Mt/yr, followed by 2.0 Mt/yr from manure left on pasture, 0.4 Mt/yr from manure management and 0.2 Mt/yr from aquaculture (Tian *et al*. 2024).

Between 1980 and 2020, direct agricultural emissions grew from 3.5 Mt in 1980 to 6.1 Mt in 2020. All four sources within the agricultural sector increased, with the largest contribution from direct soil emissions, increasing from 1.7 Mt in 1980 to 3.3 Mt in 2020, followed by emissions from manure left on pasture, 1.4–2.2 Mt; manure management, 0.38–0.41 Mt; and aquaculture, 0.02–0.2 Mt over the same period (Tian *et al*. 2024).

2.2.2 Indirect emissions from anthropogenic nitrogen additions

Indirect anthropogenic emissions result from nitrogen from human sources being deposited on land and ocean, as well as from nitrogen leaching and runoff from soils into streams, and inland and coastal waters.

In the 2010s, total indirect emissions contributed 19 per cent to the total with a decadal mean of 1.9 Mt/yr, of which 1.1 Mt/yr was from land; 0.6 Mt/yr from inland, estuary and coastal waters; and 0.2 Mt/yr from the open ocean.

Over the past four decades, total indirect nitrous oxide emissions steadily increased from 1.4 Mt in 1980 to 2.0 Mt in 2020. Emissions from nitrogen deposition on land made the largest contribution with an increase of 0.5 Mt/yr or 60 per cent compared to 1980 levels. Anthropogenic emissions from inland, estuary and coastal waters showed a small but significant increase of 0.2 Mt/yr or 33 per cent relative to 1980 levels, while emissions from nitrogen deposition on the open ocean remained unchanged (Tian *et al.* 2024).

Total agricultural and related emissions are the sum of direct and indirect emissions, and currently amount to approximately 75 per cent of anthropogenic emissions.

2.2.3 Non-agricultural emissions (direct from industry, fossil fuel combustion, landfills and wastewater)

Sources of non-agricultural direct emissions include i) fossil fuel combustion; ii) chemical industry; iii) landfills; and iv) wastewater. Emissions from non-agricultural sources made the second largest contribution to the total anthropogenic emission, with a decadal mean of 2.2 Mt/yr in the 2010s. Over the past four decades, the net emissions from this category showed 21 per cent increase from 1.9 Mt in 1980 to 2.3 Mt in 2020. Fossil fuel emissions, however, increased significantly, by 175 per cent from 0.4 Mt in 1980 to 1.1 Mt in 2020. Conversely, industrial emissions decreased, by 46 per cent from 1.3 Mt in 1980 to 0.7 Mt in 2020. This decrease in emissions has been driven primarily by the installation of abatement technology in certain Organisation for Economic Co-operation and Development (OECD) countries. However, emissions are also reported to be increasing in other countries as demand for nitric and adipic acid continue to increase (Davidson and Winiwarter 2023).

2.2.4 Emissions from burning biomass

Nitrous oxide emissions from burning biomass include those related to human activities as well as wildfires and it is difficult to separate them, but in total these emissions amounted to 1.3 Mt/yr in the 2010s. There are, however, large uncertainties in the magnitude and temporal trend of emissions from burning biomass, a substantial portion of which are not directly associated with human activities (Tian *et al*. 2024).

2.2.5 Nitrous oxide flux perturbations due to climate, carbon dioxide and land-use/land-cover change

Nitrous oxide fluxes are also affected by land-use/land-cover changes and anthropogenic perturbations to climate and atmospheric carbon dioxide. These changes in fluxes are referred to as perturbation fluxes. In terrestrial ecosystems, perturbation fluxes are caused by increasing carbon dioxide concentrations; climate change, for example, warming-induced thawing of permafrost; and land-use/land-cover change. Increased carbon dioxide levels can boost plant growth and nitrogen uptake, potentially leading to the more efficient use of nitrogen and reduced nitrous oxide emissions. The relationship between carbon dioxide and nitrous oxide emissions is, however, complex and influenced by multiple factors including changes in plant growth, soil moisture and temperature. Climate effects encompass all processes by which climate changes directly and indirectly influence nitrous oxide emissions. When forest is cleared, especially tropical forest with a significant natural nitrous oxide source, there is an initial pulse of high emissions, called a post-deforestation pulse effect. Following deforestation, the long-term effect can be either an increase or a decrease in natural nitrous oxide emissions depending on the type and outcome of the land-use change (Tian *et al.* 2024.). Deforestation followed by conversion to cropland, particularly with the use of nitrogen fertilisers, can lead to increased nitrous oxide emissions.

In the 2010s, these perturbations led to net negative nitrous oxide emissions of -0.8 Mt/yr, as the emissions reduction from deforestation of -2.2 Mt/yr and increasing carbon dioxide concentrations of -1.1 Mt/yr were partially offset by increased emissions of 1.1 Mt/yr due to the climate effect and 1.4 Mt/yr from the post-deforestation pulse effect. Perturbation fluxes became more negative over the past four decades, from -0.6 Mt/yr of nitrous oxide in 1980 to -1.0 Mt/yr in 2020 (Tian *et al*. 2024).

2.3 NATURAL EMISSIONS AND SINKS

Natural emissions are defined in this Assessment as those that would occur in the absence of human perturbations, such as anthropogenic nitrogen input and land-use/land-cover change. The largest natural source is from soils, which contribute 10 Mt/yr of nitrous oxide, approximately 54 per cent of the total natural source (Tian *et al*. 2024). Tropical rainforests have the largest rates of natural soil emissions due to moist soils, high rates of decomposition and soil nitrogen availability (Werner *et al*. 2007; Meurer *et al*. 2016; Pärn *et al.* 2018). There is a lot of variation between tropical forests, however, with the Amazon Basin having significantly larger emissions and the Congo Basin significantly smaller emissions (D'Amelio *et al*. 2009; Barthel *et al.* 2022). There is variation between years, driven largely by changes in annual rainfall (Werner *et al*. 2007), and likely related to climate variations such as El Niño Southern Oscillation (ENSO) (Ishijima *et al.* 2009; Thompson *et al*. 2014). Temperate and high latitude soils emit significantly less nitrous oxide than tropical rainforests owing to lower temperatures, lower rates of decomposition of organic matter and thus lower overall annual availability of mineral nitrogen. High rates of nitrous oxide emissions have, however, been observed from thawing permafrost peatlands, where bare soil is exposed to the atmosphere and is thought to result from the absence of soil nitrogen uptake by plants, high nitrogen mineralisation rates and favourable soil moisture (Repo *et al*. 2009; Maruschak *et al.* 2011; Voigt *et al.* 2017). It is thought that areas with high probability for nitrous oxide emissions cover 25 per cent of the Arctic and thus these emissions may amount to 0.2 Mt/yr globally (Repo *et al*. 2009) but the uncertainty in this estimate is very high because of the sparsity of measurements and the uncertainty about the area of bare soil surfaces in permafrost peatlands (Voigt *et al.* 2017).

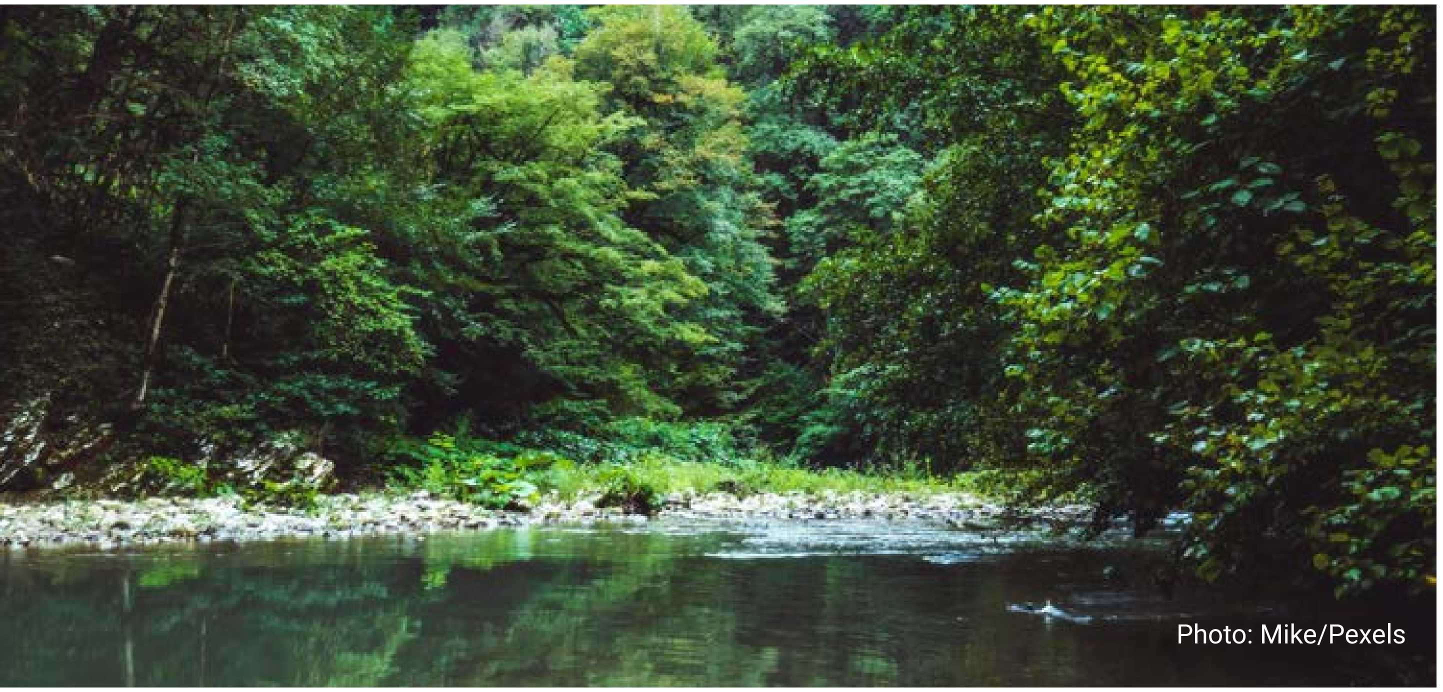
Photo: Mike/Pexels

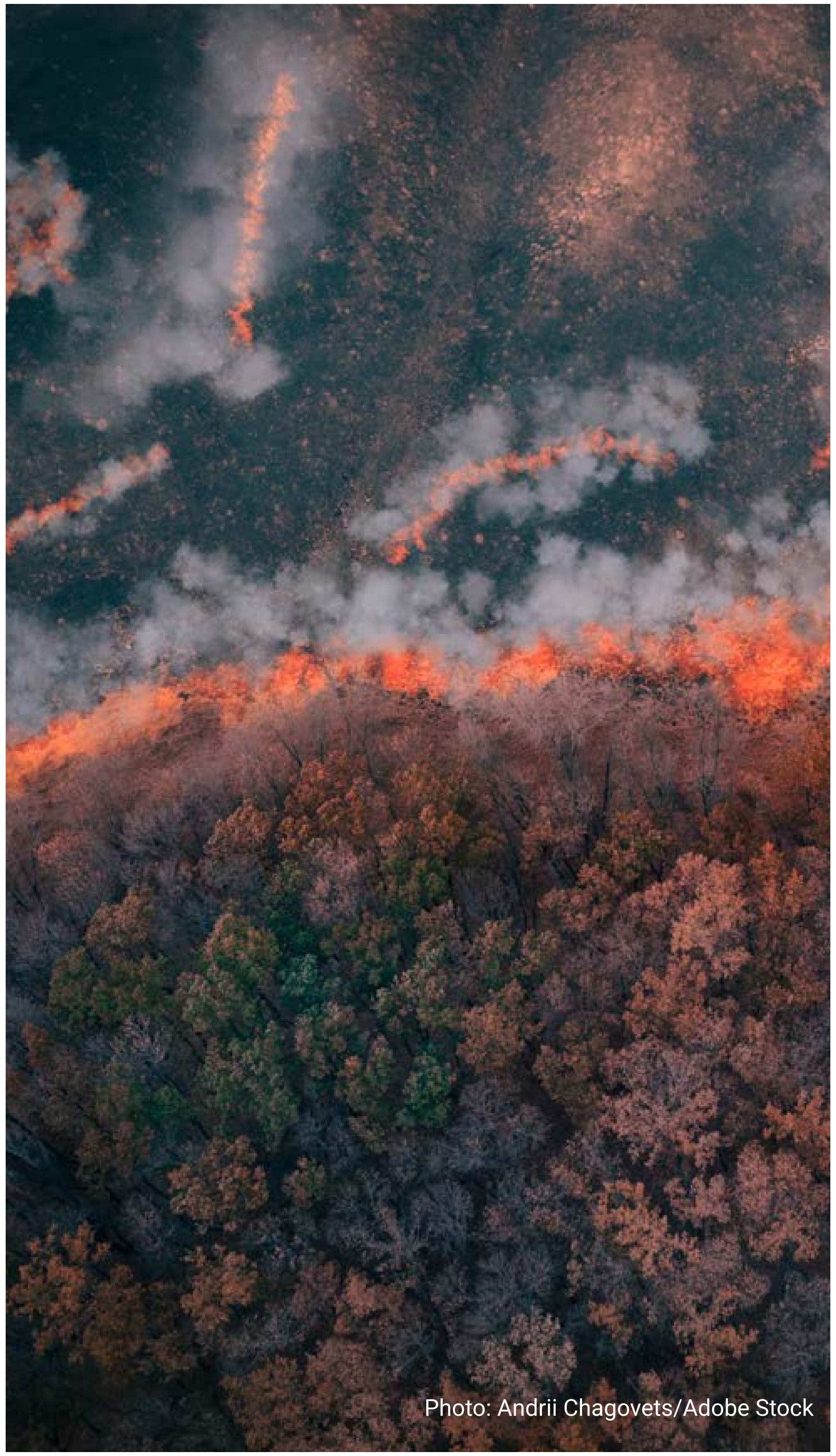
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Table 2.1 Global anthropogenic nitrous oxide emissions, 1980, 2010–2019 and 2020, megatonnes per year

UNIT	MT/YR	1980			2010 - 2019			2020		
		mean	min.	max.	mean	min.	max.	mean	min.	max.
DIRECT AGRICULTURAL EMISSIONS	Direct soil emissions	1.7	1.5	1.9	3.1	2.5	3.8	3.3	2.7	4.1
	Manure left on pasture	1.4	0.8	2.0	2.0	1.3	2.8	2.2	1.4	3.0
	Manure management	0.4	0.3	0.4	0.4	0.3	0.5	0.5	0.3	0.5
	Aquaculture	0.0	0.0	0.0	0.2	0.0	0.5	0.2	0.0	0.5
	Subtotal	**3.5**	**2.6**	**4.4**	**5.7**	**4.1**	**7.5**	**6.1**	**4.4**	**8.0**
DIRECT NON-AGRICULTURAL EMISSIONS	Chemical industry	1.3	1.3	1.3	0.7	0.6	0.8	0.7	0.6	0.9
	Fossil fuel combustion	0.4	0.4	0.4	1.0	0.9	1.1	1.1	0.8	1.3
	Waste and wastewater	0.2	0.2	0.2	0.5	0.5	0.5	0.5	0.5	0.5
	Subtotal	**1.9**	**1.9**	**1.9**	**2.2**	**2.0**	**2.4**	**2.3**	**1.9**	**2.7**
INDIRECT EMISSIONS FROM ANTHROPOGENIC NITROGEN ADDITIONS	Inland waters, estuaries, coastal vegetation	0.4	0.2	0.5	0.6	0.2	0.8	0.6	0.2	0.9
	Atmospheric N deposition on land	0.8	0.7	0.9	1.1	0.9	1.3	1.2	0.9	1.4
	Atmospheric N deposition on ocean	0.2	0.1	0.3	0.2	0.2	0.3	0.2	0.2	0.3
	Subtotal	**1.4**	**1.0**	**1.7**	**1.9**	**1.3**	**2.4**	**2.0**	**1.3**	**2.7**
EMISSIONS FROM BIOMASS BURNING*	**Biomass burning**	**1.3**	**0.8**	**1.9**	**1.3**	**0.8**	**1.6**	**1.2**	**0.8**	**1.4**
PERTURBED FLUXES FROM CLIMATE, CO_2, LAND-COVER CHANGE	CO_2 effect	-0.6	-1.0	0.3	-1.1	-2.4	0.5	-1.2	-2.5	0.5
	Climate effect	0.5	0.1	1.6	1.1	0.3	1.9	1.4	0.6	2.8
	Post-deforestation pulse effect	1.3	1.0	1.7	1.4	0.6	2.0	1.2	0.6	2.0
	Long-term effect of reduced mature forest area	-1.8	-1.6	-2.1	-2.2	-2.0	-2.5	-2.4	-2.2	-2.5
	Subtotal	**-0.6**	**-1.5**	**1.5**	**-0.8**	**-3.5**	**1.9**	**-1.0**	**-3.5**	**2.8**
TOTAL ANTHROPOGENIC EMISSIONS		**7.6**	**4.8**	**11.4**	**10.3**	**4.7**	**15.7**	**10.6**	**4.9**	**17.6**

* Biomass burning emissions include both natural and human-caused fires, with a significant portion of these emissions not linked ot human activities

Note: The total number may not always match the sum of all individual numbers due to rounding.

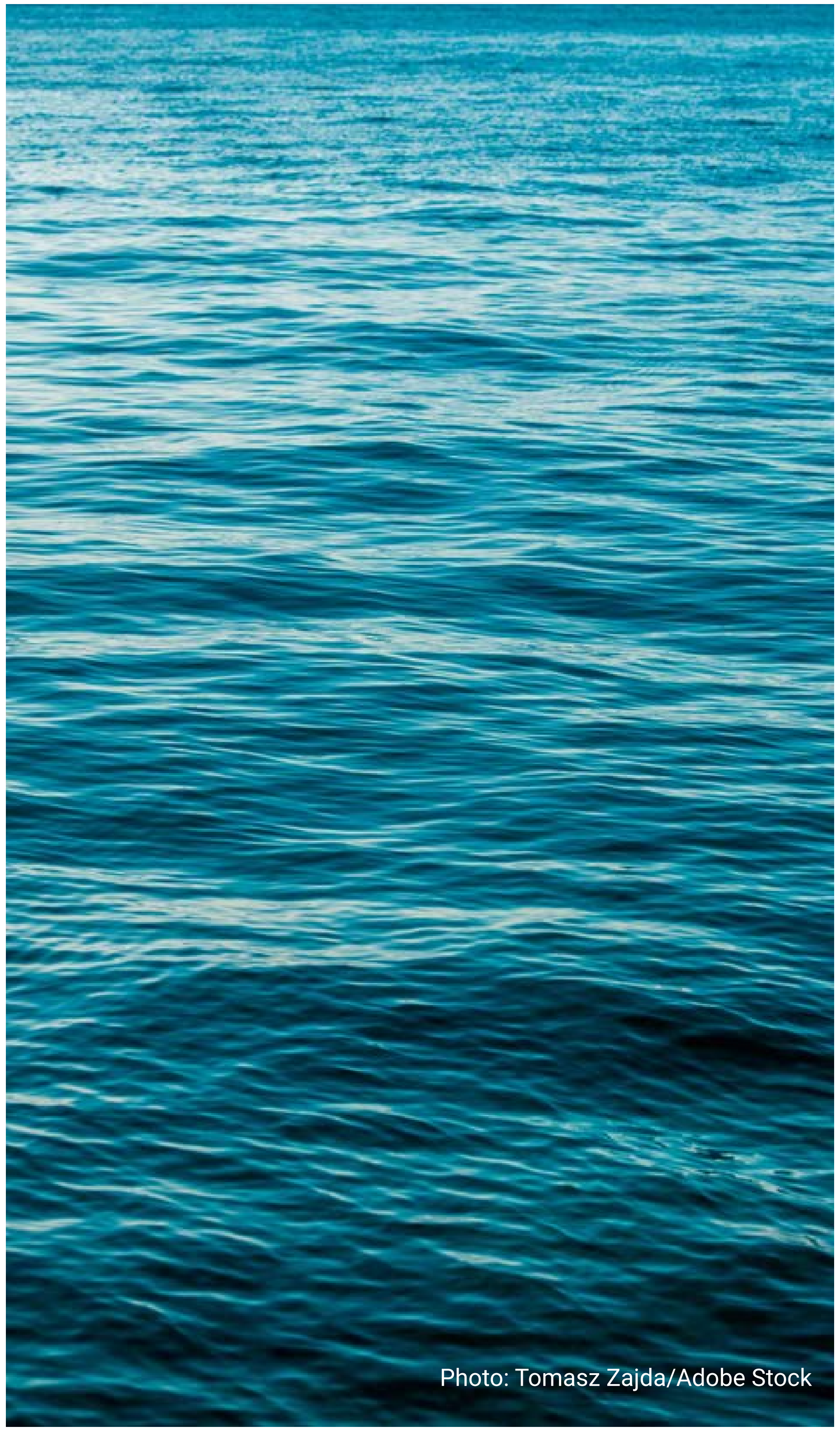
Photo: Tomasz Zajda/Adobe Stock

Oceans, including coastal shelves and the open ocean, are the second largest natural source of nitrous oxide, contributing 7.5 Mt/yr, about 37 per cent of the total natural source (Tian *et al.* 2024). The ocean emissions of nitrous oxide are, similar to soils, due to the microbial processes of nitrification and denitrification occurring below the surface (Manizza *et al*. 2012). Emissions from the ocean fluctuate from year to year, largely due to the impact of ENSO on ocean upwelling in the eastern Pacific (Nevison *et al*. 2005, Ishijima *et al*. 2009, Thompson *et al.* 2014).

The remaining natural sources of nitrous oxide only contribute a small fraction to the total source. Inland waters, including rivers, lakes and estuaries, emit 0.13 Mt/yr, of which rivers contribute the most, around 0.06 Mt/yr (Tian *et al.* 2024). Termite mounds are also a source of nitrous oxide and can have very high emission rates; rates of up to 100 times the surrounding soils have been observed (Brümmer *et al.* 2009). It is largely unknown, however, how much termites contribute to natural emissions globally owing to a lack of observations.

Photo: Philippedonn/Pexels

The atmosphere is also a small but uncertain source of nitrous oxide (Dentener and Crutzen 1994; Kohlmann and Poppe 1999; WMO 2022). The atmospheric production of nitrogen oxides due to lightning is an indirect source of nitrous oxide (Schumann and Huntrieser 2007; Nault *et al*. 2017). In total, the direct and indirect atmospheric sources are estimated to contribute 0.9 Mt/yr (Tian *et al*. 2024).

The primary sink of nitrous oxide is through photochemical reactions in the stratosphere – a process that also leads to the production of nitric oxide and contributes to stratospheric ozone depletion (Crutzen 1970; Minschwaner *et al.* 1993). Globally, this sink amounts to 21.0 Mt/yr resulting in a mean atmospheric lifetime of nitrous oxide of about 116±9 years (Prather *et al.* 2015; Prather *et al*. 2022). In addition, uptake of nitrous oxide by soils has been observed and mostly occurs in wetlands and peatlands, but global estimates of this sink vary widely from <0.1–0.5 Mt/yr (Chapuis-Lardy *et al.* 2007; Syakila *et al.* 2011; Schlesinger 2013).

2.4 REGIONAL EMISSIONS BREAKDOWN AND TRENDS

Nitrous oxide emission trends and sectoral contributions are examined for 10 regions, which encompass all countries. The regions were defined considering the similarity of the country-level nitrous oxide emission trends and economic development, while keeping each region contiguous (Figure 2.4). The estimates and trends are based on the comprehensive estimates of the Global Carbon Project (Tian *et al.* 2024). More detail on the regions, and included countries, is given in the supplementary information (SI 2.2).

Photo: Dimazel/Adobe Stock

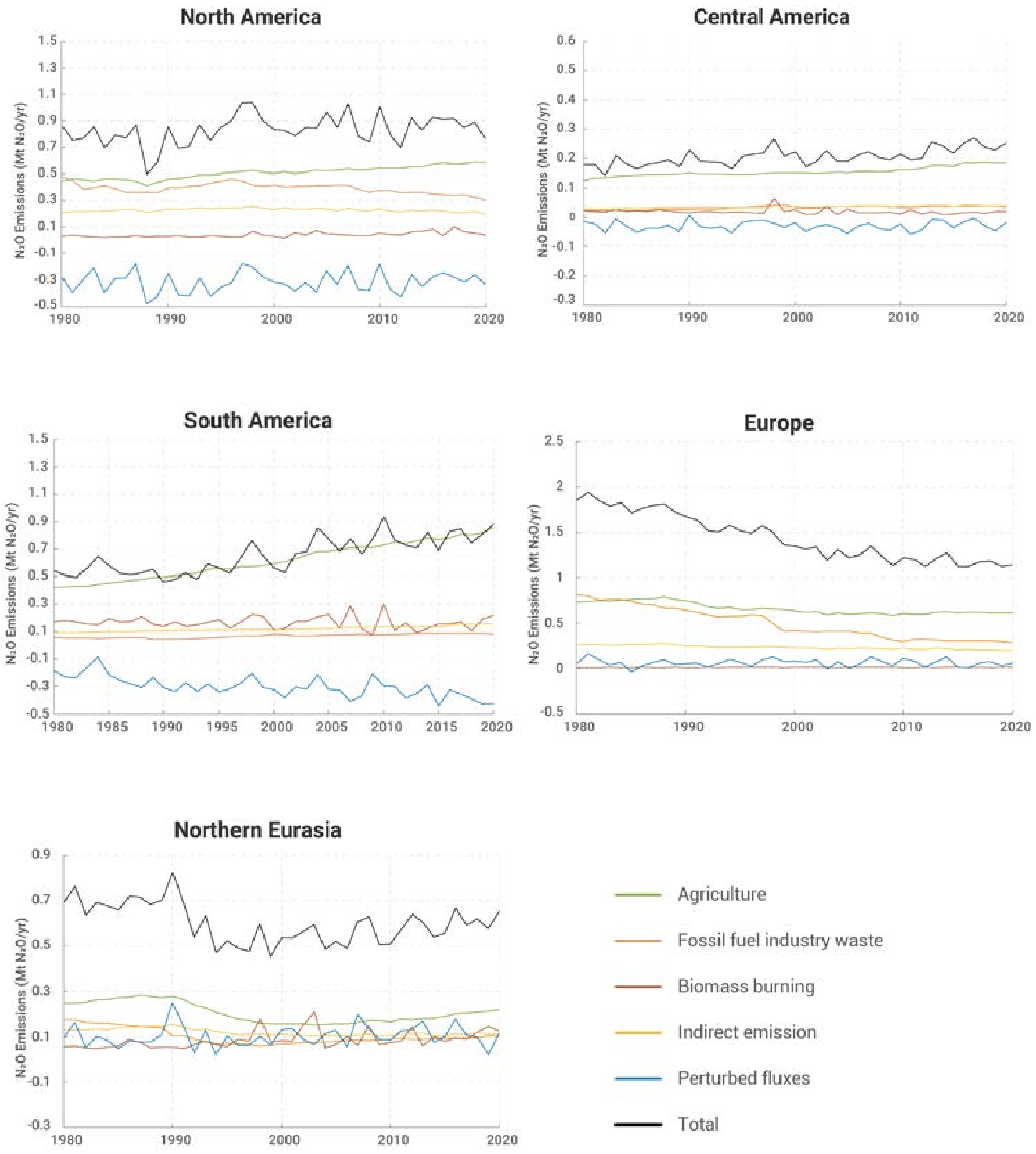

Figure 2.4 A Ensembles of regional anthropogenic nitrous oxide emissions, 1980–2020, megatonnes of nitrogen per year.
Note: Different y-axis scales are used to highlight the small emissions from the three regions: Australasia, Central America, and Northern Eurasia.

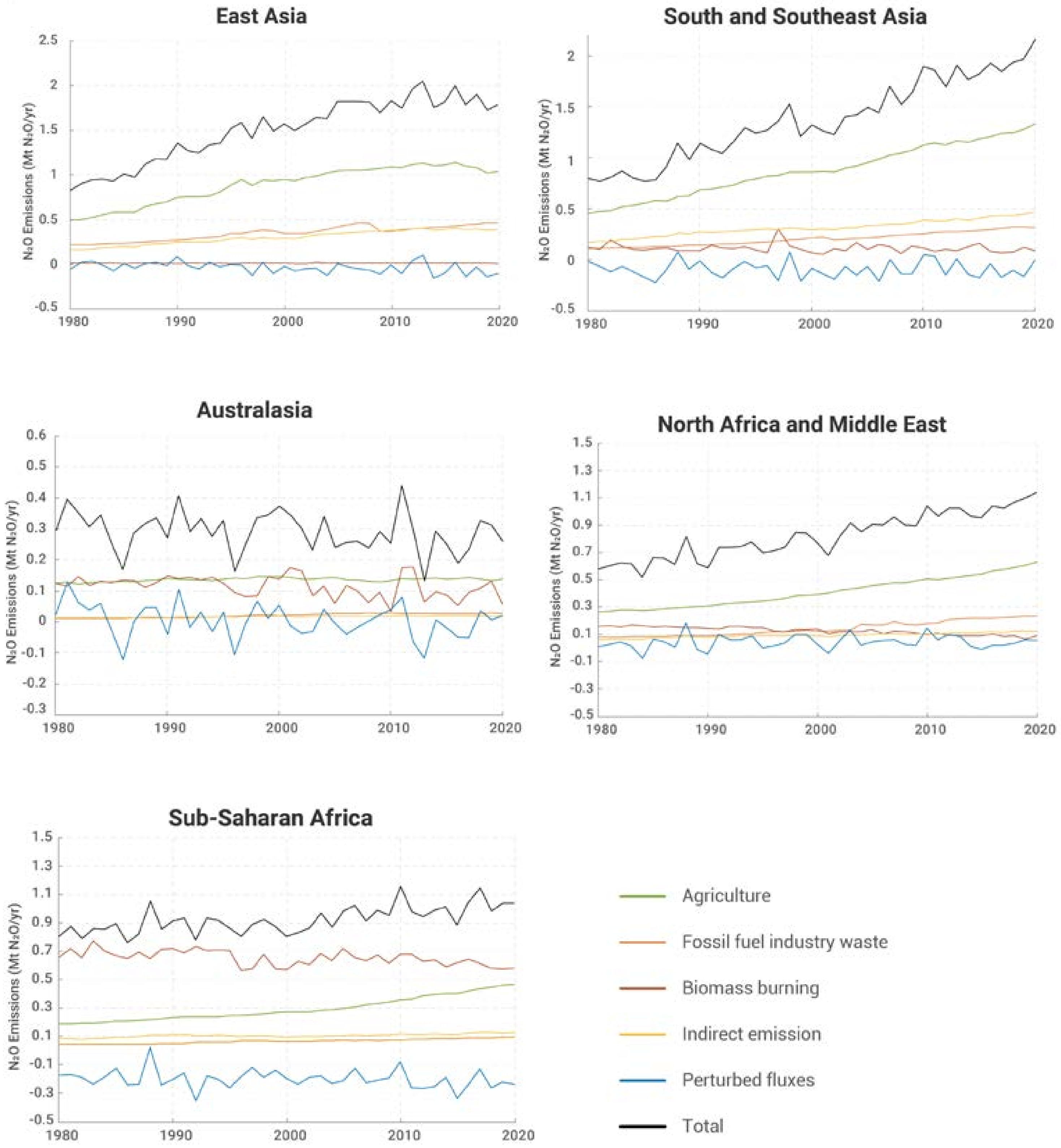

Figure 2.4 B Ensembles of regional anthropogenic nitrous oxide emissions, 1980–2020, megatonnes of nitrogen per year.
Note: Different y-axis scales are used to highlight the small emissions from the three regions: Australasia, Central America, and Northern Eurasia.

Photo: Borishamer/Pexels

2.4.1 North America

The total emissions from North America are estimated to be on average 1.72 Mt/yr for the 2010s, of which natural sources contribute 0.88 Mt/yr. The net anthropogenic emissions were 0.84 Mt/yr, which was the balance of direct and indirect emissions (1.11 Mt/yr) as well as a negative contribution from changes in land-use/land-cover, carbon dioxide and climate (-0.28 Mt/yr).

Direct agricultural emissions were the most important anthropogenic source contributing 0.53 Mt/yr to the net anthropogenic emissions, emissions from fossil fuels, industry, landfills and wastewater together contributed 0.33 Mt/yr, while indirect emissions from anthropogenic nitrogen additions contributed 0.20 Mt/yr. Emissions from biomass burning made a relatively small contribution of 0.06 Mt/yr.

Total anthropogenic nitrous oxide emissions decreased by 0.05 Mt/yr from 1980 to 2020, equivalent to a decrease of 10 per cent, with most of the reduction occurring after the late 1990s. This decrease was primarily from reductions in fossil fuel, industry, landfill and wastewater emissions, which decreased by 0.16 Mt/yr. A small decrease of 0.02 Mt/yr was also seen in indirect emissions but these were largely offset by increases in direct agricultural emissions which increased by 0.13 Mt/yr. Changes in climate, carbon dioxide and land-use/land-cover change remained relatively stable with a mean of -0.30 Mt/yr for the period 1980–2020.

2.4.2 Central America

Total nitrous oxide emissions from Central America were estimated to be 0.49 Mt/yr in the 2010s, of which natural sources contributed 0.27 Mt/yr and net anthropogenic sources 0.22 Mt/yr. Direct agricultural emissions were the most important anthropogenic source contributing 0.17 Mt/yr. The remaining anthropogenic sources were small in comparison, with emissions from fossil fuels, industry, landfills and wastewater contributing to 0.03 Mt/yr, indirect sources contributing 0.03 Mt/yr, and biomass burning 0.02 Mt/yr. Changes in climate, carbon dioxide and land-use/land cover had an overall negative effect on nitrous oxide emissions with a mean value of -0.03 Mt/yr.

Overall anthropogenic emissions increased between 1980 and 2020 with direct agricultural emissions driving this trend with an increase of 0.06 Mt/yr, equivalent to 40.8 per cent. Emissions from fossil fuels, industry, landfills and wastewater increased by 0.02 Mt/yr, while indirect emissions, emissions from biomass burning, and perturbed fluxes from changes in climate, carbon dioxide and land cover have remained relatively stable over the last four decades.

2.4.5 South America

Total nitrous oxide emissions from South America were 3.43 Mt/yr in the 2010s. Natural sources contributed 2.65 Mt/yr during this period while the net anthropogenic contribution was 0.78 Mt/yr. Tropical forest soils in South America were the largest natural source of nitrous oxide. Emissions from agriculture were the most important direct source contributing 0.77 Mt/yr, while indirect sources and biomass burning each contributed 0.14 Mt/yr. Emissions from fossil fuels, industry, landfills and wastewater only contributed 0.08 Mt/yr. Changes in climate, carbon dioxide, and land use/land cover had an overall negative effect on nitrous oxide emissions, with the mean value of -0.35 Mt/yr.

Anthropogenic emissions of nitrous oxide increased by 0.25 Mt/yr between 1980 and 2020, an increase of 61.3 per cent. This was driven by direct agricultural emissions, which increased by 0.42 Mt/yr while indirect emissions played a more minor role increasing by 0.06 Mt/yr. On the other hand, emissions from biomass burning, fossil fuels, industry, landfills and wastewater were relatively stable. Changes in climate, carbon dioxide and land cover a resulted in a larger negative emission of -0.42 Mt/yr in 2020, compared to -0.19 Mt/yr in 1980.

2.4.4 Europe

European nitrous oxide emissions in the 2010s amounted to 1.6 Mt/yr, of which natural sources made a relatively minor contribution of 0.41 Mt/yr. Direct agricultural emissions were the largest anthropogenic source contributing 0.60 Mt/yr, followed by emissions from fossil fuels, industry, landfills and wastewater, and indirect emissions contributing 0.30 Mt/yr and 0.20 Mt/yr, respectively. Biomass burning was an almost negligible source at 0.06 Mt/yr. Changes in climate, carbon dioxide and land cover had an overall positive effect on nitrous oxide emissions with a mean value of 0.03 Mt/yr.

Between 1980 and 2020, anthropogenic emissions decreased by 0.71 Mt/yr, a decrease of 38.8 per cent. Non-agricultural direct emissions decreased by 0.52 Mt/yr, the largest contribution to the trend, driven largely by a decrease in industrial emissions. Direct agricultural emissions and indirect emissions also decreased by 0.13 Mt/yr and 0.06 Mt/yr, respectively. The decreasing trend in direct agricultural emissions has, however, levelled off since 2000. Emissions from changes in climate, carbon dioxide and land use/land cover varied from year to year with no significant trend between 1980 and 2020.

2.4.5 Northern Eurasia

Northern Eurasian nitrous oxide emissions were 1.41 Mt/yr for the 2010s. Natural sources contributed 0.82 Mt/yr during this period, while emissions from direct agricultural sources were 0.19 Mt/yr; indirect sources, 0.11 Mt/yr, and biomass burning, 0.09 Mt/ yr; and emissions from fossil fuels, industry, landfills and wastewater, 0.09 Mt/yr. Changes in climate, carbon dioxide and land use/land cover had an overall positive effect on nitrous oxide emissions with a mean value of 0.11 Mt/yr.

Total anthropogenic nitrous oxide emissions deceased by 0.05 Mt/yr from 1980 to 2020, a decrease of 6 per cent. Direct agricultural emissions decreased from 0.25 Mt/yr in 1980 to 0.14 Mt/yr in 2003, then increased to 0.22 Mt/yr in 2020. Emissions from fossil fuels, industry, and waste and wastewater decreased by 0.08 Mt/yr between 1980 and 2020. Emissions from biomass burningand perturbation fluxes from changes in climate, carbon dioxide and land use/land cover had large interannual variabilities with no clear trend over the last four decades.

2.4.6 East Asia

East Asian nitrous oxide emissions were 2.39 Mt/yr in the 2010s. Natural sources contributed 0.50 Mt/yr to the total emissions. Direct agricultural emissions were the dominant source, contributing to 1.11 Mt/yr, almost 60 per cent of anthropogenic emissions. Emissions from indirect sources contributed 0.39 Mt/yr and fossil fuels, industry, landfills and wastewater emissions 0.42 Mt/yr while emissions from biomass burning contributed less than 0.02 Mt/yr. Changes in climate, carbon dioxide and land cover had an overall negative effect on nitrous oxide emissions with a mean value of -0.05 Mt/yr.

Total anthropogenic nitrous oxide emissions increased by 0.97 Mt/yr from 1980 to 2020, an increase of 117.3 per cent. Direct agricultural emissions made the largest contribution, increasing by 0.64 Mt/yr from 1980 to 2016 but then decreased by 0.09 Mt/yr to 2020 due to decreased nitrogen fertiliser application, particularly in China. Both indirect emissions and emissions from fossil fuels, industry, landfills and wastewater increased continuously by 0.24 Mt/yr and 0.25 Mt/yr, respectively. Perturbed fluxes from changes in climate, carbon dioxide and land cover did not show a significant trend.

2.4.7 South and Southeast Asia

Total nitrous oxide emissions from South and Southeast Asia, amounted to 3.30 Mt/yr in the 2010s, of which natural sources contributed 1.43 Mt/yr. Emissions from direct agricultural sources were the most important anthropogenic source contributing 1.18 Mt/yr, while indirect sources and emissions from fossil fuels, industry, landfills and wastewater contributed to 0.41 Mt/yr and 0.28 Mt/yr, respectively. Biomass burning contributed only 0.09 Mt/yr. Changes in climate, carbon dioxide and land use/land cover had an overall small negative effect on nitrous oxide emissions with a mean value of -0.09 Mt/yr.

Total anthropogenic nitrous oxide emissions increased by 1.37 Mt/yr from 1980 to 2020, equivalent to an increase of 172 per cent. Direct agricultural emissions increased by 0.88 Mt/yr over the period and were the majordriver of the increase in the region. Emissions from fossil fuels, industry, landfills and wastewater, and indirect emissions also continuously increased, by 0.21 Mt/yr and 0.30 Mt/yr, respectively. Changes in climate, carbon dioxide and land use/land cover led to a minor increase of 0.01 Mt/yr. Emissions from biomass burning decreased by 0.03 Mt/yr, though with significant interannual variability.

2.4.8 Australasia

Total nitrous oxide emissions were 0.67 Mt/yr in the 2010s, of which 0.39 Mt/yr were from natural sources. Direct agricultural emissions were the largest anthropogenic source amounting to 0.14 Mt/yr, while emissions from indirect sources were 0.02 Mt/yr; 0.11 Mt/yr from biomass burning; and 0.03 Mt/yr from fossil fuels, industry, landfills and wastewater. Changes in climate, carbon dioxide and land cover had an overall negative effect on nitrous oxide emissions with a mean value of -0.02 Mt/yr.

Total anthropogenic nitrous oxide emission decreased by 0.04 Mt/yr between 1980 and 2020, a decrease of 12 per cent. During the last four decades emissions changed little: direct agricultural emissions increased by 0.02 Mt/yr and there were negligible alterations in emissions from biomass burning or from changes in climate, carbon dioxide and land use/land cover, although there was significant interannual variability in these last categories.

2.4.9 North Africa and the Middle East

Total nitrous oxide emissions from North Africa and the Middle East were 1.59 Mt/yr in the 2010s, of which natural sources accounted for 0.57 Mt/yr. Direct agricultural sources were the largest anthropogenic source contributing 0.55 Mt/yr. Emissions from fossil fuels, industry, landfills and wastewater provided 0.22 Mt/yr, while indirect sources and biomass burning were significantly smaller, contributing 0.11 Mt/yr, and 0.09 Mt/yr, respectively. Changes in climate, carbon dioxide and land use/land cover had an overall positive effect on nitrous oxide emissions with a mean value of 0.05 Mt/yr.

From 1980 to 2020, there was a considerable increase in anthropogenic emissions of 0.55 Mt/yr, 96 per cent, largely driven by direct agricultural emissions, which increased by 0.36 Mt/yr. Emissions from fossil fuels, industry, landfills and wastewater increased by 0.16 Mt/yr, and indirect emissions also increased by 0.06 Mt/yr. In contrast, emissions from biomass burning decreased by 0.06 Mt/yr while emissions from changes in climate, carbon dioxide and land use/land cover in the region remained relatively stable.

2.4.10 Sub-Saharan Africa

Emissions from Sub-Saharan Africa were 3.14 Mt/yr in the 2010s, with natural sources making the largest contribution of 2.12 Mt/yr. Of anthropogenic emissions, direct agricultural sources contributed 0.41 Mt/yr, while indirect sources, contributed about 0.13 Mt/yr. Emissions from fossil fuels, industry, landfills and wastewater contributed only 0.08 Mt/yr. Biomass burning emissions accounted for 0.62 Mt/yr, however, which includes emissions from both natural and human-caused fires. Changes in climate, carbon dioxide and land use/land cover had an overall negative effect on nitrous oxide emissions with a mean value of -0.22 Mt/yr.
From 1980 to 2020, total anthropogenic emissions increased by 0.24 Mt/yr, 29 per cent, with direct agricultural emissions increasing by 0.28 Mt/yr and thus drove the trend (Omotoso and Omotayo 2024). Emissions from fossil fuels, industry, landfills and wastewater increased by 0.05 Mt/yr, and indirect emissions increased by the same amount. Emissions from biomass burning decreased by 0.08 Mt/yr, while perturbed fluxes from changes in climate, carbon dioxide and land use/land cover did not alter significantly but had large interannual variability.


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CHAPTER 3:

NITROUS OXIDE SCENARIOS AND ABATEMENT MEASURES

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KEY MESSAGES

1. Three scenarios evaluate the impacts of future nitrous oxide emissions, based on representative concentration/shared socioeconomic pathway (RCP/SSP) combinations and nitrogen-specific scenarios developed for the forthcoming *International Nitrogen Assessment*.

2. Under the reference scenario, which assumes a continuation of current trends in nitrogen production, consumption and loss, nitrous oxide emissions increase by approximately 30 per cent by 2050 and 110 per cent by 2100, relative to 2020. Under the technical reductions scenario, based on the implementation of all currently available technologies and practices, emissions decrease by approximately 20 per cent by 2050 and 15 per cent by 2100, relative to 2020. Under the technical reductions and societal change scenario, which considers additional transformative changes including dietary shifts towards the lower consumption of animal protein, emissions decrease by approximately 40 per cent by 2050 and 60 per cent in 2100, relative to 2020.

3. Limitations of current scenarios, and their model implementation, include the fact that current nitrous oxide emissions trends are higher than the highest reference scenarios, which is not the case for carbon dioxide and methane, meaning that the current envelope of nitrous oxide futures is likely too narrow. Furthermore, scenarios that extrapolate from past emissions trends or rely on existing abatement measures and production systems inherently fail to account for more transformative change, particularly to the global food system. Finally, there is a key research gap regarding the potential trade-offs between carbon dioxide, methane and nitrous oxide abatement associated with several emerging decarbonisation technologies, including the use of ammonia as a fuel and bioenergy production.

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3.1 INTRODUCTION

This chapter outlines the scenario framework underpinning this Assessment. Scenarios are an opportunity to explore a range of possible futures. Nitrogen is at the heart of many environmental scenarios given its multiple impacts as a pollutant and its key role in food, energy and industrial production (Bouwman *et al*. 2009; van Vuuren *et al.* 2011; UNEP 2013; Bodirsky *et al.* 2014; Mogollon *et al.* 2018).

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This Assessment adopts the widely used Representative Concentration Pathways and Shared Socioeconomic Pathways (RCPs/SSPs) combinations as the foundation for the 2020–2100 impact analysis detailed in chapter 4 (Popp *et al.* 2017; Riahi *et al*. 2017; Rao *et al.* 2017). The SSPs are one of the most important and widely applied scenario frameworks in environmental science and policy – a set of five storylines describing a range of societal trajectories defined by socio-economic, demographic, technological, lifestyle, policy, institutional and other drivers (Riahi *et al.* 2017). Combined with the four RCPs which span a range of radiative forcing futures and thus greenhouse gas emission trajectories (Moss *et al.* 2010), they form the backbone of the climate projections used in the Intergovernmental Panel on Climate Change's (IPCC) Fifth and Sixth Assessment Reports (IPCC 2014; IPCC 2021). The broad basis of the SSP framework enables their application across a range of other environmental issues including ozone layer protection, air pollution, ecosystem services, land use and water (e.g. Mouratiadou *et al.* 2016; Popp *et al.* 2017; Rao *et al.* 2017; Mogollon *et al.* 2018; van Puijenbroek *et al.* 2019). While the RCP/SSPs do not include nitrogen-specific measures and interventions, they do account for the major drivers of nitrogen production, consumption and loss, including food, feed and fibre, fossil fuels and wastewater.

For the period 2020–2050, this Assessment supplements the RCP/SSP scenarios with nitrogen-specific scenarios, which lay out the additional effects of implementing nitrogen-specific abatement action sector by sector (Kanter *et al*. 2020). They represent low, moderate and high levels of nitrogen policy ambition that require increasingly stringent implementation of a range of nitrogen-specific interventions and measures. They cover all major nitrogen compounds, including nitrous oxide, and were developed for the forthcoming *International Nitrogen Assessment* (INA). Their singular focus on nitrogen allows for the consideration of abatement action directly concentrated on nitrogen pollution and nitrous oxide to 2050, thereby presenting a more concrete set of medium-term futures for scientists, policymakers and other stakeholders.

Beyond 2050, this Assessment relies solely on the RCP/SSP combinations detailed below. Assessing impacts to 2100 is critical because it enables the evaluation of the short- to medium-term effects of a sustainable nitrogen management approach to nitrous oxide mitigation on air quality, as well as the longer-term effects on climate and the stratospheric ozone layer. The other nitrogen-related impacts of these scenarios, including the impacts on water quality and ecosystem health, are evaluated extensively in the INA.

3.2 SCENARIOS

3.2.1 Scenario overview protocol

This Assessment evaluates three broad scenarios, covering 2020–2100, that capture a wide envelope of potential nitrous oxide emissions trajectories. They are referred to throughout this Assessment as the reference, technical reductions and technical reductions and societal change scenarios. The scenarios are summarised in Table 3.1 and illustrated in Figure 3.1.

Table 3.1 Summary of the composition of the three scenarios underpinning this Assessment

	SCENARIO					
	Reference		Technical reductions		Technical reductions and societal change	
TIMEFRAME	2020-2050	2050-2100	2020-2050	2050-2100	2020-2050	2050-2100
RCP/SSP COMBINATION	RCP 4.5/ SSP 2	RCP 7.0/ SSP 3	RCP 4.5/ SSP 2	RCP 2.6/ SSP 1	RCP 2.6/ SSP 1	RCP 1.9
NITROGEN POLICY AMBITION (TO 2050)	Low	N/A	High	N/A	High + dietary change	N/A

Note: The scenarios specifications underpinning the climate and ozone layer impacts are detailed in chapter 4. The RCP/SSP combinations used under “technical reductions and societal change” scenario are slightly different for the evaluation of ozone and climate impacts, respectively. For the ozone impacts, this assessment uses RCP 2.6/SSP1, and for the climate impacts it uses RCP 1.9.

For the reference scenario, which assumes a continuation of current nitrogen production, consumption and loss trends, the RCP/SSP combination is RCP 4.5/SSP 2 from 2020 to 2050 coupled with low nitrogen-policy ambition, and RCP 7.0-SSP 3 from 2050 to 2100. For the technical reductions scenario, which assumes that all improvements in nitrogen management and nitrous oxide abatement that could be implemented using existing technologies and practices are indeed implemented, the RCP/SSP combination is RCP 4.5/ SSP 2 coupled with a high nitrogen-policy ambition from 2020 and 2050, continuing with RCP 2.6/SSP1 from 2050–2100. For the technical reductions and societal change scenario, which adds dietary change and other transformative changes beyond 2050, the RCP/SSP combination is RCP 2.6/SSP 1 coupled with high nitrogen-policy ambition and dietary change from 2020 to 2050, and RCP 1.9 from 2050 through 2100. Figure 3.1 shows the overall emissions trends of these three different scenarios. In order to isolate the effect of nitrous oxide on climate, this Assessment holds all other non-carbon dioxide emissions to their RCP 4.5/SSP 2 trajectories across the three scenarios.

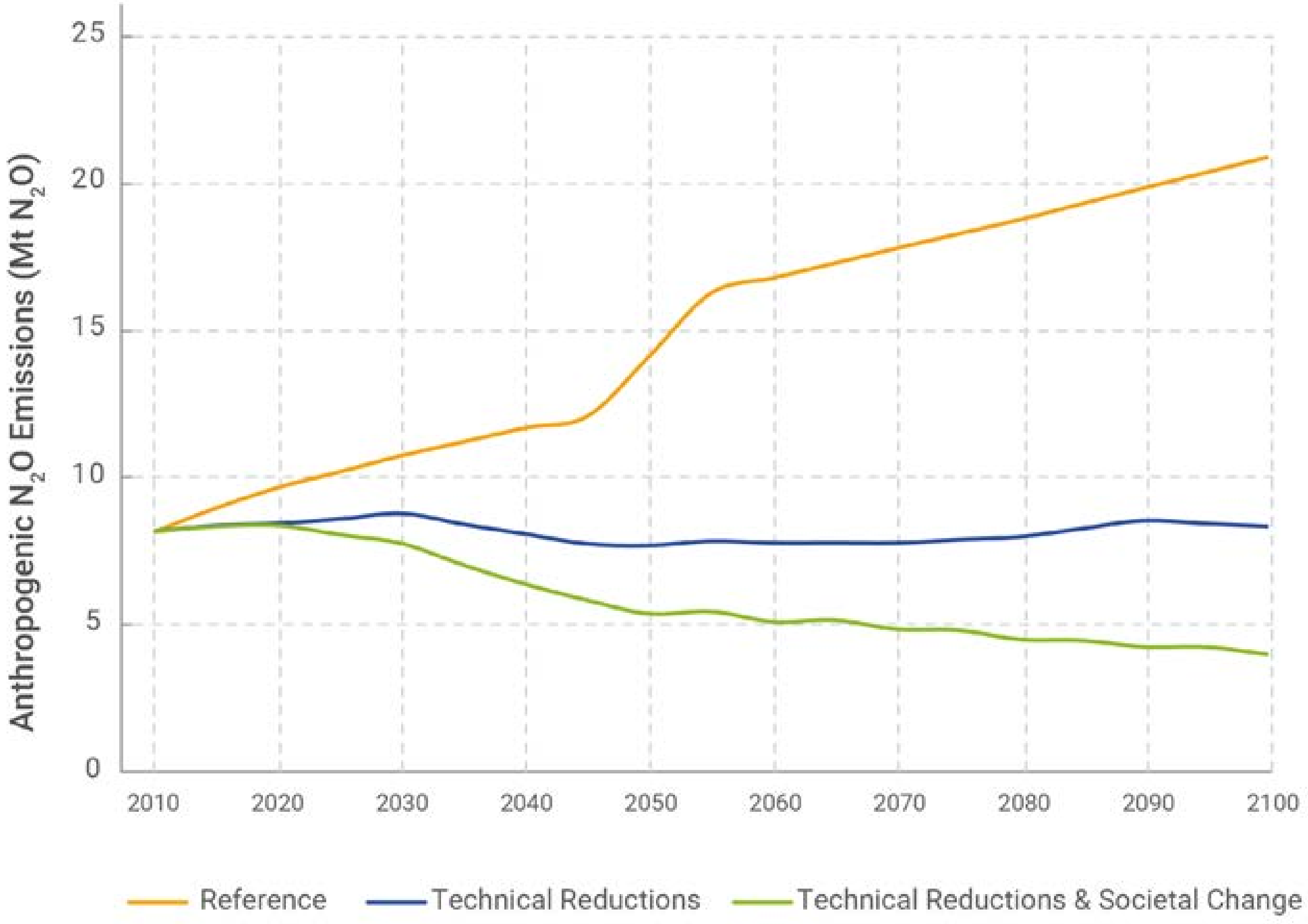

Figure 3.1 Emissions trends for the three scenarios evaluated as part of this Assessment

Note: The jump in emissions in the reference scenario between 2045 and 2050 is due to the transition from the RCP 4.5/SSP 2 with low policy ambition combination from 2020 to 2050 to the RCP 7.0/SSP 3 combination for 2050–2100. This assessment uses the IIASA emissions trajectories for the INA scenarios, which only go to 2050. For the 2050-2100 period we use RCP-SSP combinations only, which are slightly different, hence the jump in emissions seen in 2050.

3.2.2 Scenarios: from present day to 2050

The nitrogen-specific scenarios to 2050 used in this Assessment were developed by the *International Nitrogen Management System*[3] series of processes and projects and form the basis of the analysis of nitrogen impacts in the forthcoming International Nitrogen Assessment (Kanter *et al*. 2020). For this Assessment, the scenarios were implemented by the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, an integrated assessment model that estimates abatement costs and potentials for air pollution and greenhouse gas mitigation (Winiwarter *et al.* 2018). The technical specifications associated with each scenario and how they were implemented in the IIASA GAINS model are described in Table 3.3, while the nitrous oxide emissions associated with each scenario to 2050 are listed in Table 3.2. Table 3.4 summarises the major abatement measures that would need to be implemented for the more ambitious scenarios to be realised. For further information on these abatement measures see Sutton *et al.* (2022), Brownlie *et al.* (2024) and Chapter 24 of the forthcoming *International Nitrogen Assessment.*


Photo: Akos Szabo/Pexels

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[3] https://inms.international/

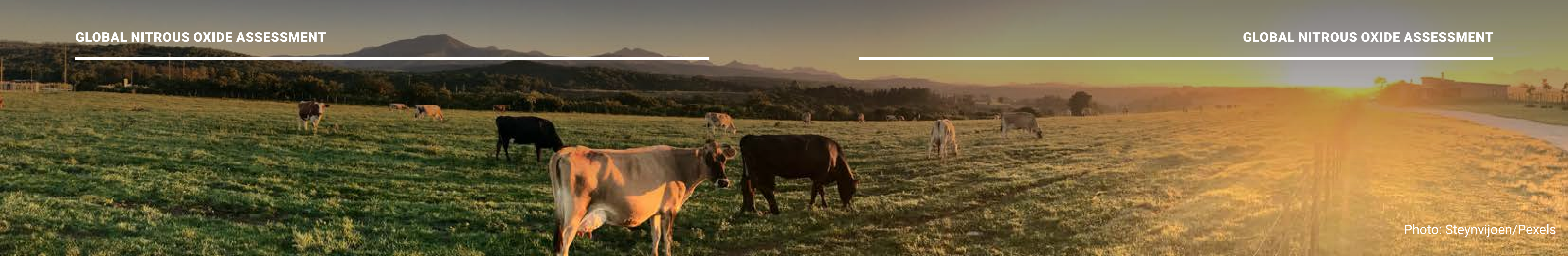


Photo: Steynvijoen/Pexels

GAINS bases its analysis on its own emissions inventory and abatement data that IIASA has collected and analysed (Winiwarter *et al.* 2018), but it should be noted that considerable differences in emissions estimates exist for some sectors and countries. Estimates in the GAINS model of industrial nitrous oxide emissions in China for 2010–2020, for example, are approximately 50 per cent lower compared to a recent Chinese study (Liang *et al*. 2024). Reconciling these differences is a key research priority outlined in Chapter 6 of this Assessment. An evaluation of how the GAINS implementation of the INMS Scenarios compare with the IMAGE and MAgPIE integrated assessment models is provided in Chapters 13 and 27 of the forthcoming *International Nitrogen Assessment*.

The nitrogen-specific scenarios use the RCP/SSP paired scenarios as a foundation, and then build on them by adding low, moderate and high levels of nitrogen-policy ambition that require increasingly stringent implementation of a range of nitrogen-specific interventions and measures. While several different combinations of RCP/SSPs and nitrogen-policy ambition levels are evaluated in the forthcoming *International Nitrogen Assessment*, this Assessment uses low ambition policy for the reference scenario and high policy ambition for both the technical reductions and technical reductions and societal change scenarios (Table 3.1).

High ambition policy represents the frontier of technical feasibility in a timeframe largely consistent with the Sustainable Development Goals (SDGs), which run until 2030, while low ambition represents either no improvement or a continuation of current trends, which can be negative, for example, decreasing nitrogen-use efficiency (NUE). Given country differences in economic and agronomic circumstances, the nitrogen-specific scenarios use three country groups, defined by their economic wellbeing and nitrogen-use intensity, with three corresponding sets of nitrogen policy trajectories:
i) Organisation for Economic Co-operation and Development (OECD) countries; ii) non-OECD countries with moderate to high nitrogen use, defined as an annual nitrogen surplus (i.e., the balance between nitrogen inputs and outputs) greater than 50 kilograms of nitrogen per hectare (kg N/ha); and iii) non-OECD countries, with low nitrogen use, defined as an annual nitrogen surplus of less than 50 kg N/ha, based on data from Zhang *et al.* (2015).

For crop production, the nitrogen-specific scenarios use NUE to measure progress. Nitrogen-use efficiency is the ratio of nitrogen in harvested crop biomass to total nitrogen inputs from synthetic fertiliser, manure, biological nitrogen fixation and atmospheric nitrogen deposition. This ratio can be increased by either reducing nitrogen surpluses and/or improving plants' nitrogen uptake. For the purposes of the scenarios, each country has a national-level NUE target taken from Zhang *et al*. (2015), which is consistent with returning or keeping crop nitrogen surpluses within a proposed nitrogen planetary boundary (Richardson *et al.* 2023). The different nitrogen-policy ambition levels represent different years and/or economic development levels in which these national NUE targets are achieved, for example, 2030 for OECD countries in the high policy ambition scenario. National NUE targets range from 0.6 to 0.75 (Zhang *et al.* 2015) and can be achieved using a range of existing technologies and practices, including precision agriculture, split application and enhanced-efficiency fertilisers. They do not prescribe or assume a particular combination of technologies or practices given the vast heterogeneity of agricultural nitrogen levels and management across the world. Indeed, this heterogeneity means that some countries have very high nitrogen surpluses and low NUE, leaving ample opportunity for reducing nitrogen losses from agriculture, while other countries have close to zero nitrogen surpluses and high NUE, often exceeding 1.0,

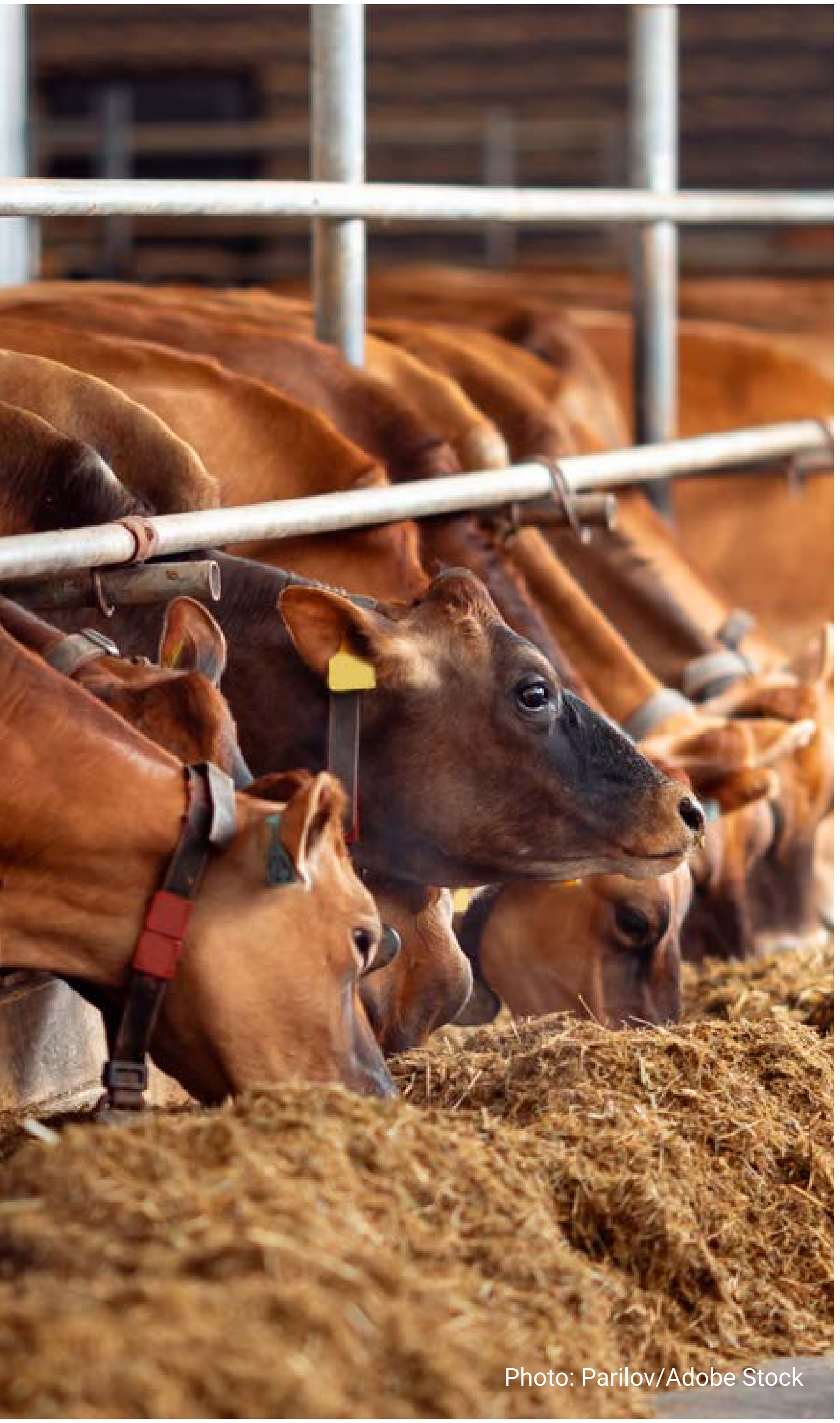


Photo: Parilov/Adobe Stock

indicating that more nitrogen is removed in harvests than is replaced by inputs. For the latter, agricultural soils are being depleted of nitrogen due to insufficient nitrogen inputs, causing low yields, as is the case in much of Sub-Saharan Africa. In these cases, nitrogen inputs can and should be increased to improve productivity even if this is accompanied by small increases in nitrogen losses to the environment (GEOBON 2022).

For livestock production, the nitrogen-specific scenarios use both excretion per unit of animal product (kilograms of nitrogen excreted per tonne meat, milk or eggs) and manure recycling rates. Improving the latter requires increasing and improving manure capture, storage, treatment and utilisation, while excretion rates can be reduced through improvements in animal breeding, feed quality and management, animal health and herd management (UNEP 2013). Under high ambition policies, OECD countries reduce excretion rates by up to 30 per cent by 2050 and achieve 90 per cent recycling for manure that can feasibly be collected by 2030 or double recycling rates by 2050, depending on the country context (see Kanter *et al.* (2020) for details). Non-OECD countries achieve similar targets at later dates depending on economic development trends.

Photo: AZ Studio/Adobe Stock

For dietary change and food loss and waste, the technical reductions and societal change scenario adopts the most ambitious projections from Springmann *et al.* (2018): by 2050 food loss and waste is reduced by 75 per cent from current levels, and a shift towards diets based on strict limits for red and white meat as well as dairy, and high minimum amounts of legumes, nuts and vegetables (Willett *et al.* 2019). Given that these transitions depend as much on changes in consumer behaviour as they do on technical developments, such as better farm storage facilities, these scenarios apply the assumption of Springmann *et al.* (2018) that these targets and timelines apply equally across all countries.

For industrial nitrous oxide emissions, by 2050, the IIASA GAINS implementation of the technical reductions and technical reductions and societal change scenarios assumes the following by 2050: that all nitrous oxide emissions from global adipic acid production are 99 per cent abated, and that nitrous oxide from all OECD-based nitric acid production and half of non-OECD based production is 95 per cent abated. Finally, for wastewater, the IIASA GAINS implementation of the technical reductions and technical reductions and societal change scenarios assumes that by 2050 all wastewater in OECD countries and half of wastewater in non-OECD countries is processed to minimise nitrous oxide losses, resulting in 40 per cent lower nitrous oxide emissions than untreated wastewater.

Photo: Jeremy Bishop/Pexels

3.2.2 Scenarios: from 2050 to 2100

In order to assess the impacts of nitrous oxide emissions beyond 2050, the reference, technical reductions and technical reductions and societal change scenarios in this Assessment use RCP/SSP combinations without additional nitrogen-specific interventions from 2050 to 2100. The reference scenario uses the RCP 7.0/SSP 3 storyline, which has the highest reference marker emissions for nitrous oxide. The technical reductions scenario uses RCP 2.6/SSP 1, while technical reductions and societal change uses RCP 1.9, with the latter developed specifically for the IPCC's assessment of the 1.5° C temperature goal.

Nitrous oxide emissions reductions beyond 2050 in the technical reductions and societal change scenarios are approximately 20 per cent lower than can be achieved by 2050, relative to 2020. These additional reductions can likely only be achieved by more transformative changes in global food, industrial, transport and social systems (see Chapter 5). These kinds of transformations would likely have multiple co-benefits, as well as additional abatement costs and societal barriers (see Chapter 5), enhancing the likelihood of achieving a number of Sustainable Development Goals (Kanter and Brownlie 2019), including SDG 2 (End hunger), SDG 6 (Clean water for all), SDG 12 (Sustainable consumption and production) and SDG 13 (Climate action).

Photo: Lovelyday12/Adobe Stock

Table 3.2 Nitrous oxide emissions by sector for the three INA scenarios to 2050, by sector, tonnes per year

SECTOR	Reference scenario 2020 emissions (t N_2O/yr)	Reference scenario 2050 emissions (t N_2O/yr)	Technical reductions 2050 emissions (t N_2O/yr)	Technical reductions and societal change 2050 emissions (t N_2O/yr)
ADIPIC AND NITRIC ACID	470,000	649,000	46,000	46,000
LIVESTOCK AND MANURE	799,000	1,013,000	1,013,000	693,000
CROPLANDS AND GRASSLANDS	6,593,000	8,660,000	4,860,000	3,546,000
WASTEWATER	774,000	975,000	547,000	547,000
TOTAL (INCLUDING SECTORS NOT LISTED)	9,669,000	12,442,000	7,540,000	5,444,000

Note: The total is the sum of all sectors, including sectors, such as heating, transport, medical and food uses, not directly evaluated in this Assessment.
* This estimate is about 8 per cent lower than that of Tian *et al*. (2024), which is summarised in Chapter 2, because it excludes biomass burning, climate change feedbacks, land-use change effects, and indirect nitrous oxide emissions from N deposition.

Table 3.3 The assumptions underpinning the IIASA GAINS implementation of the nitrogen-specific scenarios developed for the forthcoming International Nitrogen Assessment and used for this Assessment in the scenarios for 2010–2050

SCENARIO	REPRESENTATIVE CONCENTRATION PATHWAY	SHARED SOCIOECONOMIC PATHWAY	CHANGE IN FERTILISER CONSUMPTIONBY 2050 OVER 2010 (%)	CHANGES IN ANIMAL NUMBERS BY 2050 OVER 2010 (%)	NITROGEN POLICY AMBITION: DIET	INDUSTRIAL N_2O	WASTEWATER N_2O
Reference	RCP 4.5	SSP 2	90	45	Moderately meat- and dairy-rich as dictated by SSP 2	Emission trends follow industrial gross domestic product (GDP) as dictated by SSP 2	Emission trends follow population growth as dictated by SSP 2
Technical reductions	RCP 4.5	SSP 2	-41	45	Same as reference scenario	Adipic acid: All N_2O emissions 99% abated by 2050 Nitric acid: N_2O emissions from all OECD and half of non-OECD production 95% abated by 2050	All wastewater in OECD and half of wastewater in non-OECD countries is processed to minimize N_2O emissions by 40% by 2050
Technical reductions and societal change	RCP 2.6	SSP 1	-47	-7	Transition towards the EAT-Lancet diet[a] for all world regions by 2030	Same as technical reductions scenario	Same as technical reductions scenario

[a] https://eatforum.org/eat-lancet-commission/the-planetary-health-diet-and-you/

Table 3.4 Overview of example nitrogen abatement measures by sub-sector and measure sub-category that could significantly reduce nitrous oxide emissions

SUB-SECTOR	MEASURE SUB-CATEGORY	EXAMPLE MEASURE(S)	RELIABILITY	TECHNICAL REQUIREMENTS
Cropland	N testing	Soil and plant nitrogen testing	Robust	High
	N application rates	Split application Controlled-release fertilisers; urease and nitrification inhibitors; reduced application rates; increase manure recycling	Robust	Intermediate
	Crop management	Integrate N-fixing crops in rotations; reduced tillage; cover crops	Robust	Basic
Livestock	Livestock diets	Optimise protein intake	Robust	Basic
	Grazing	Rotational grazing	Robust	Basic
	Manure storage/ processing	Solid/slurry separation; Storage under dry conditions and rapid drying; Anaerobic digestion	Promising Robust	High Intermediate
Landscape	Drainage control	Buffer strips	Promising	Basic
	Planning	Integration of crop and livestock production	Promising	Basic
Industrial	Adipic acid production	Catalytic reduction; Thermal destruction	Robust	High
	Nitric acid production	Catalytic reduction; Thermal destruction	Robust	High
Wastewater		Process optimisation to increase N_2/N_2O ratio	Robust	High

3.2.4 Limitations of current scenarios

A significant limitation of the nitrous oxide scenarios used in this Assessment and elsewhere is that current anthropogenic nitrous oxide emissions and atmospheric concentrations exceed even the highest emissions scenario (Figure 3.2). Consequently, the range of possible nitrous oxide futures evaluated in this Assessment are likely too narrow and future scenario efforts need to develop new storylines that significantly expand the scope of possible anthropogenic nitrous oxide emissions trajectories. This is further underlined where scenarios continue to assume low nitrogen application rates in such as regions Sub-Saharan Africa out to 2100 but without significant increases in nitrogen use efficiency. This points to the need for further development of future scenarios that account for both changing nitrogen application rates and nitrogen use efficiency rates, especially given large projected regional population growth and food production needs.

In addition, scenario development is frequently constrained by the capacity of different models, whether integrated assessment, earth systems, crop or other models, to implement the different storylines. with sometimes limited integration with social and behavioural models. This is especially the case with more transformative changes, such as the reintegration of crop and livestock production in many parts of the world, genetic engineering of plants, novel sources of nitrogen in animal feed, greatly improved manure recycling, and agroecology/regenerative agricultural approaches. Such transformative changes, which should also account for the different effects on gender where possible, need to be integrated into future scenarios and models in order to provide stakeholders a clearer understanding of the full range of options available and their environmental and socioeconomic implications.

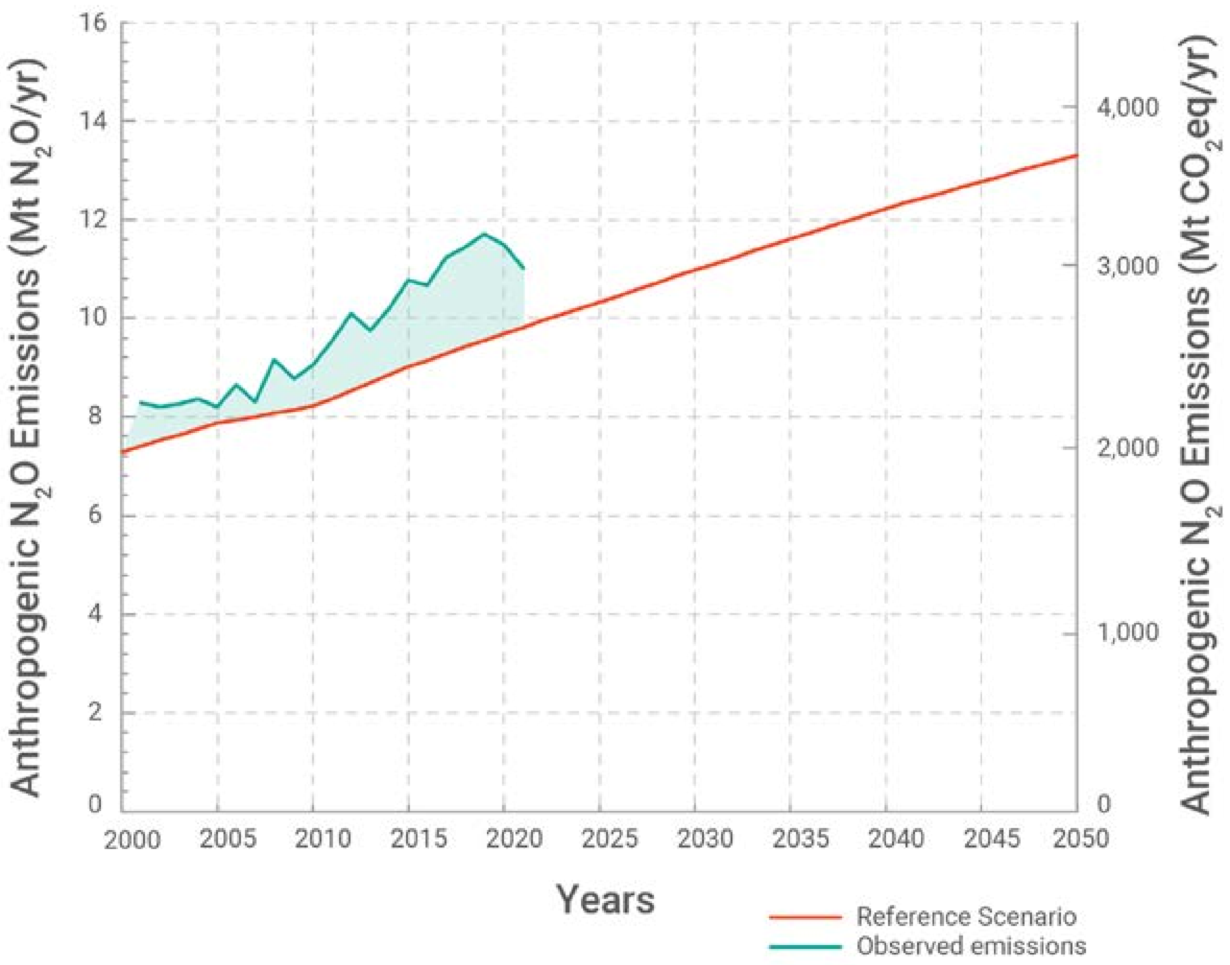


Figure 3.2 Observed anthropogenic nitrous oxide emissions (smoothed; teal) compared with the reference scenario (red) evaluated in this Assessment

Finally, it is critical to enhance the quantification and assessment of the impacts of emerging decarbonisation technologies on nitrogen use and nitrous oxide emissions, especially given the increasing push for these technologies. The carbon dioxide and methane mitigation benefits of some decarbonisation technologies and practices could be partially or even completely offset by increases in nitrous oxide emissions if pre-emptive policy and technical action is not taken (Bertagni *et al.* 2023). A review of existing literature identified five major decarbonisation strategies that could have a profound impact on nitrogen use, several of which are likely to increase nitrogen use and consequently nitrous oxide emissions (Figure 3.3; Zhang *et al.* in press). Utilising ammonia as a fuel, for instance, could lead to an increase in nitrogen inputs, with values ranging between 0.5 and 14 kilograms of nitrogen input per kilogram of carbon dioxide mitigated. Therefore, replacing 44 per cent of the fossil fuels used in marine shipping with ammonia-based fuels, as evaluated by the International Energy Agency (IEA), could lower carbon dioxide emissions by up to 380 million tonnes annually, but would necessitate an additional 212 million tonnes of new ammonia production annually (IEA 2023). Depending on the proportion of nitrous oxide and nitrogen oxides emitted during ammonia combustion, using ammonia as a marine shipping fuel could have a carbon footprint comparable to other renewable energy sources or higher than coal (Bertagni *et al*. 2023). In a similar vein, achieving carbon dioxide mitigation of 0.7 (± 0.3) billion tonnes of carbon dioxide equivalent per year through the use of biofuels would necessitate an additional 21–42 million tonnes of nitrogen being applied annually to croplands. These initial assessments are subject to considerable uncertainty, and the associated risks are not represented in current nitrous oxide scenarios, underscoring the need for these issues to be addressed in future nitrogen scenarios.

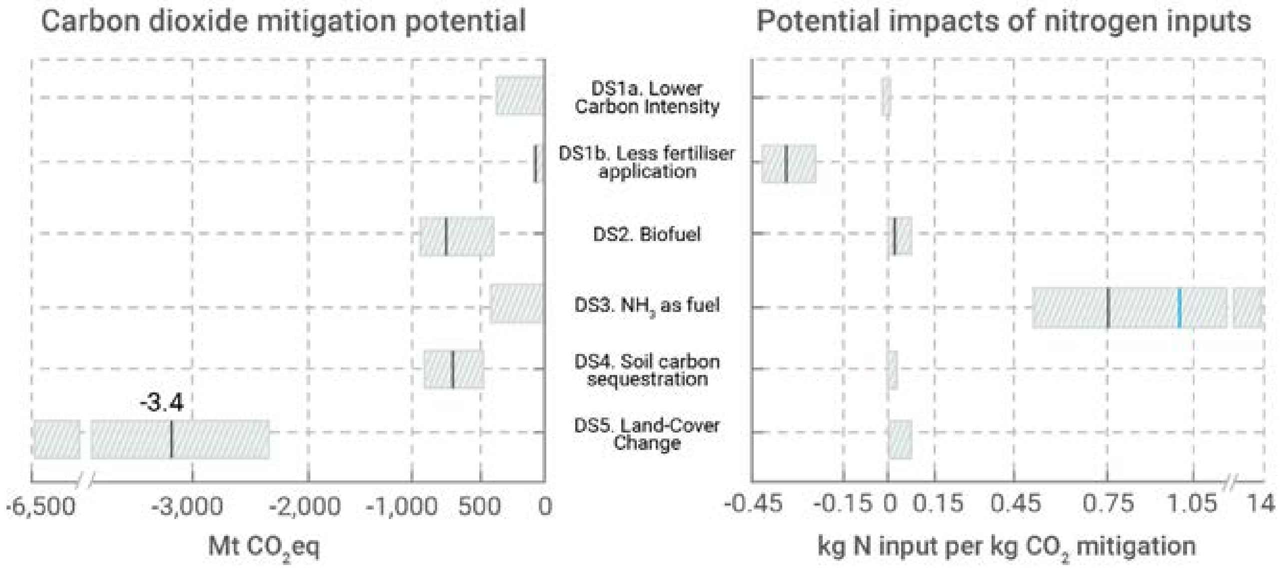
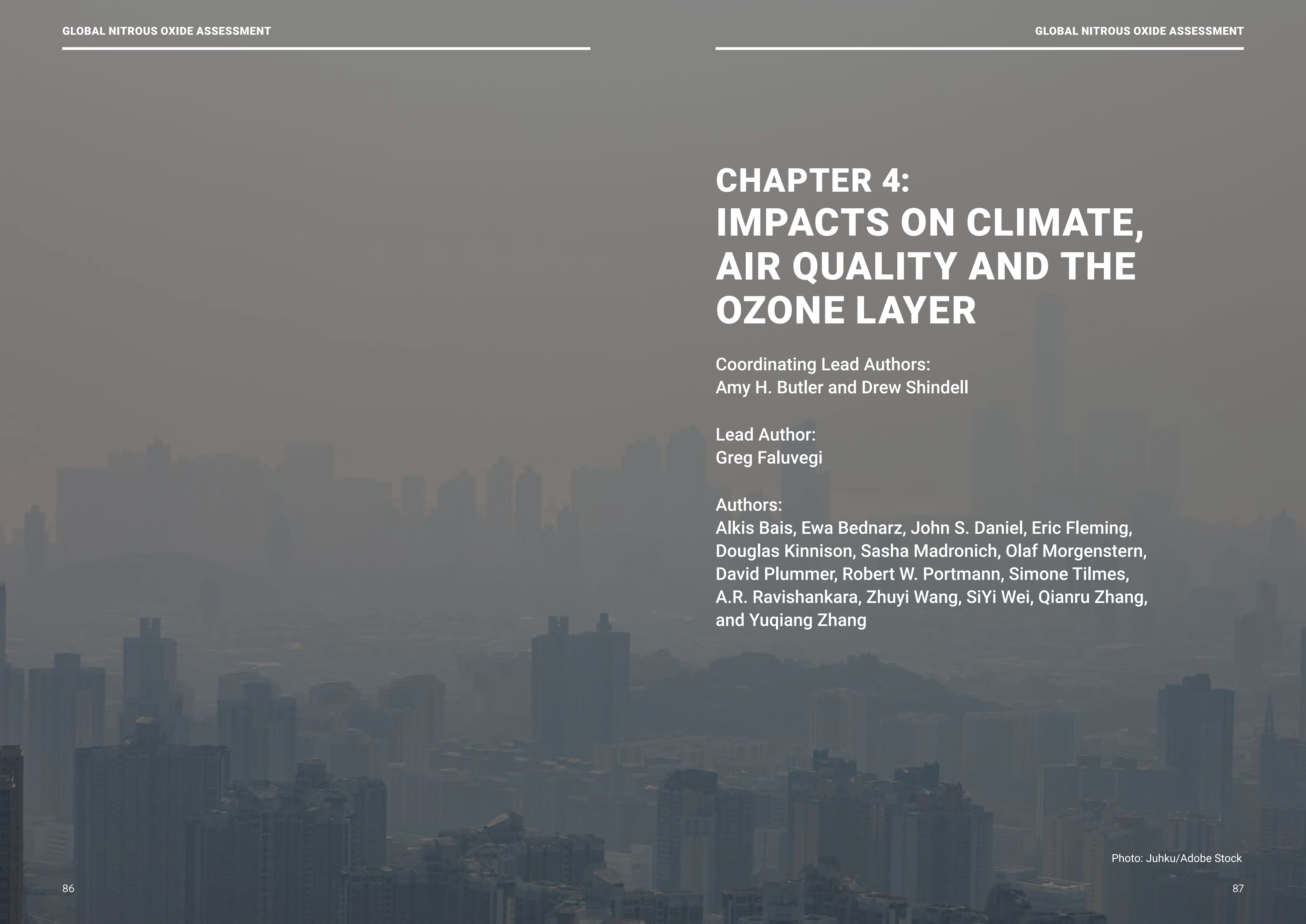


Figure 3.3: The impacts of five decarbonisation strategies for reducing carbon dioxide emissions and nitrogen inputs per kilogram of carbon dioxide reduction. The left panel illustrates the carbon dioxide mitigation potential of each decarbonisation strategy. In the right panel, negative values indicate reduction in nitrogen inputs associated with a kilogram of carbon dioxide reduction

Note: Uncertainty ranges of carbon dioxide mitigation potential (Mt CO_2eq/yr) and nitrogen impacts (kilograms of nitrogen input per kilogram of carbon dioxide mitigation) are shown in dashed gray box with averaged impact highlighted using a black line. Two solid lines in DS3 correspond to average values for ammonia produced from solar (blue) and wind (black) energy, respectively. Positive nitrogen impacts (right panel) suggest that the nitrous oxide emissions from nitrogen use could offset or even exceed the climate benefits of carbon dioxide mitigation (left panel). The actual net impact on climate depends on the nitrous oxide emission factors, which remain highly uncertain.

Source: Left panel: IPCC 2022; IEA 2021, 2023; Rosa and Gabrielli 2023; Zhang *et al.* 2015: Right panel: Zhang *et al.* in press



CHAPTER 4:

IMPACTS ON CLIMATE, AIR QUALITY AND THE OZONE LAYER

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KEY MESSAGES

Climate and air quality impact

1. The Paris Agreement's temperature goals, which require maintaining net-zero or net-negative emissions of long-lived greenhouse gases, primarily carbon dioxide, cannot be sustainably achieved if nitrous oxide emissions continue to increase.

2. Improved nitrogen management scenarios (Chapter 3) provide nitrous oxide abatement that is equivalent to reducing carbon dioxide emissions by up to 235 billion tonnes, helping to reach a long-term 1.5° Celsius (or 2.0 ° Celsius) goal.

3. The air quality improvements resulting from the improved nitrogen management scenarios lead to roughly 4 million avoided premature deaths due to decreased fine particulate matter and ozone exposure over the next decade, and approximately 20 million avoided premature deaths by 2050.

4. The temperature change due to the reduction of cooling aerosols associated with improved agricultural nitrogen management is likely to outweigh the impact of reduced greenhouse gases in the near-term. This would result in modest additional warming for most of the century, stressing the need to accelerate reductions in short-lived climate pollutants and carbon dioxide to counteract this impact. This is similar to the climate impacts of phasing out coal-fired electricity generation, which leads to aerosol-driven short-term warming but carbon dioxide-driven long-term reductions in warming. Reduced emissions of industrial nitrous oxide, however, would provide climate benefits over all timescales as there are minimal co-emissions.

5. If nitrogen oxide and ammonia emissions were already reduced to meet non-climate policy goals, such as air quality improvements, but nitrous oxide emissions not limited, improved agricultural nitrogen management could provide climate benefits over all timescales.

6. Without additional actions, nitrous oxide emissions would lead to around 0.2° Celsius of additional warming by the end of the century. In contrast, improved nitrogen management with technical reductions and associated livestock methane emissions reductions leads to a near-neutral climate impact by the end of the century compared with a high-end emissions scenario in which minimal action is taken. In the same context, improved nitrogen management with technical reductions and societal change as well as associated livestock methane emissions reductions leads to a 0.1° Celsius reduction in warming beginning late in this century.

Photo: Pavel/Adobe Stock

KEY MESSAGES

Nitrous oxide, stratospheric ozone depletion and its impacts

1. Nitrous oxide is currently the most significant ozone-layer depleting substance being emitted to the atmosphere. This is because anthropogenic nitrous oxide is increasing, and the Montreal Protocol has succeeded in controlling long-lived halogenated ozone-depleting substances (ODS). Without additional controls, future nitrous oxide emissions are expected to grow and to cause additional ozone depletion.

2. The benefits of mitigating nitrous oxide to ozone are much greater by the end of the century than in the near-term. Even though ambitious nitrous oxide abatement strategies only reduce nitrous oxide levels in the atmosphere by a small amount in the next two decades, the benefits accumulate over time. Because nitrous oxide remains in the atmosphere for a long time, the earlier action is taken to reduce nitrous oxide, the sooner those benefits will be realised.

3. Ambitious abatement of nitrous oxide emissions would avoid ozone depletion over the next two decades comparable to accelerating the phase down of HCFCs, an action taken by the Parties to the Montreal Protocol in 2007. It could be five times this action when accumulated until 2100.

4. Calculated global ozone depletion avoided by ambitiously abating nitrous oxide emissions, compared to unabated emissions growth, by the end of the 21st century would amount to about a quarter of the peak historical global ozone depletion caused by substances now controlled under the Montreal Protocol.

5. Ambitious nitrous oxide abatement could avoid cataract cases increasing by 0.2-0.8 per cent and squamous cell carcinoma cases by 2.2-9.8 per cent by 2080-2090, depending on latitude.

6. The lowest levels of ozone this century and beyond are expected to occur if nitrous oxide emissions continue unabated and carbon dioxide and methane are abated consistent with climate goals. In such a future, by the end of the century much of the world's population could be exposed to UV levels potentially larger than peak ozone depletion in 1995-2005.

Photo: Jakov Jovanoski/Pexels

The new analysis in this assessment focuses on the direct effects of nitrous oxide on climate change and ozone layer depletion, as well as the indirect effects on air quality of other nitrogen compounds that are often co-emitted with nitrous oxide. This assessment does not generate new quantitative estimates of the other indirect effects of nitrous oxide emissions, notably the effects on water quality or ecosystem health. More information on all of the major impacts of nitrogen pollution can be found in the forthcoming International Nitrogen Assessment.

4.1 IMPACTS ON CLIMATE AND AIR QUALITY

4.1.1 Introduction

Anthropogenic emissions of nitrous oxide come primarily from agricultural sources, with a smaller contribution from waste and industry. There has been limited progress on mitigating anthropogenic nitrous oxide emissions even though it is the third strongest driver of global warming to date, and, as it has an atmospheric residence time of more than a century, early action is essential to avoid a long-term buildup of concentrations in the atmosphere (Forster *et al.* 2021). The agricultural practices that lead to nitrous oxide emissions also drive emissions of nitrogen oxides and ammonia, often referred to as co-emissions. Industrial and waste sector nitrous oxide emissions are not associated with substantial amounts of ammonia but there are small co-emissions of nitrogen oxides.
Analysis of the effects of policies to reduce nitrous oxide emissions therefore requires assessment of the impacts of both the nitrous oxide changes and the changes in climate drivers resulting from the co-emitted species. Nitrogen oxides emissions lead to multiple changes in climate drivers in the troposphere, including increased tropospheric ozone, which causes warming; reductions in methane, due to increased formation of the oxidising hydroxyl radical, that causes cooling; and increases in both nitrate and secondary organic aerosols, which cause cooling.Ammonia emissions lead to increases in aerosols as well, causing cooling. Hence, while the direct impact of nitrous oxide reductions would be cooling, given that nitrous oxide is a powerful greenhouse gas, decreases in co-emissions primarily cause warming, often described as unmasking of greenhouse gas-induced warming due to reductions in cooling aerosols. In response to changes in emissions, the aerosols, ozone and methane responses would be rapid whereas changes in nitrous oxide would take place slowly over a century. Prior analyses of the near-present-day net climate impact of increases in species containing nitrogen relative to their preindustrial levels indicate that it is cooling, primarily as a result of the large impact of cooling aerosols (Forster *et al.* 2021; Gong *et al.* 2024). Those aerosols, however, degrade air quality, contributing to adverse public health impacts, as do the increases in surface-level ozone caused by nitrogen oxides emissions. Hence the effects of policies to reduce nitrous oxide may lead to tradeoffs between climate and air quality goals, which may also vary over time given the markedly different residence times of nitrous oxide and aerosols or ozone.

Impacts of the nitrogen scenarios on climate and air quality were evaluated with a suite o models including a set of three-member ensemble simulations of composition and climate with the Goddard Institute of Space Studies (GISS)-E2.1-G model, a single simulation of composition and climate with the Community Earth System Model (CESM) 2 model, and composition simulations with the Goddard Earth Observing System (GEOS)-Chem model (SI3).

Analysis of climate and air pollution responses to the technical reductions and technical reductions and societal change policy scenarios described in Chapter 3 included the effects of changes in both nitrous oxide and nitrous oxide emissions: agriculture, waste and chemical industry. Changes in methane emissions from the agricultural sector due to changes in livestock numbers required to achieve the nitrogen goals of the scenarios were also included in additional analyses.

4.1.2 Climate Change

Radiative Forcing

Radiative forcing is a measure of the changes in the Earth's energy balance with space that provides a useful indicator of what the eventual climate response will be and of the relative importance of different climate change drivers. An ensemble of climate model simulations for this Assessment were driven with changes in concentrations of nitrous oxide and emissions of nitrogen oxides and ammonia as noted in section 4.1.1 and included changes in ozone and aerosols in response to those emissions and concentration changes, providing diagnostics of radiative forcing for all these compounds. Additional changes would also take place which would affect climate, including changes in methane in response to altered oxidation capacity and changes in carbon dioxide in response to the effects of altered surface ozone and nitrogen deposition on ecosystems. These factors were not included in the model due to computational constraints (coupled methane and carbon cycles are more expensive to model) but were evaluated separately. In addition, nitrogen measures in the agricultural sector would also lead to changes in methane emissions from that sector. The climate impact of changes in methane from livestock associated with nitrogen measures has also been evaluated separately using a simple model of the methane cycle.

In the simulations using the GISS model, the change in radiative forcing under the scenarios with increasingly ambitious nitrogen policies is dominated by the response of aerosols, which greatly outweighs the response of greenhouse gases (Table 4.1).

Table 4.1 Radiative forcings, 2040–2050, watts per square metre

	Technical reductions versus reference scenarios (W/m^2)	Technical reductions and societal change versus reference scenarios (W/m^2)
Ozone	-0.024 ± 0.008	-0.030 ± 0.008
Aerosols (all sky)	0.131 ± 0.013	0.181 ± 0.014
Aerosols (clear sky)	0.166 ± 0.018	0.229 ± 0.025
Nitrous Oxide	-0.020 ± 0.003	-0.027 ± 0.004
Total in climate modelling	0.087 ± 0.015	0.124 ± 0.017
Methane lifetime response	0.032 ± 0.009	0.039 ± 0.010
Methane emissions from livestock	-0.019 ± 0.004	-0.088 ± 0.018
Total	0.100 ± 0.016	0.075 ± 0.022

Both nitrate and secondary organic aerosols would be expected to decrease because of the emissions reductions, the former due to a decrease in precursor nitrogen species and the latter due to a reduction in atmospheric oxidation capacity in response to cuts in nitrogen oxides. There are also small decreases in sulphate aerosols as their formation also slows in response to decreased oxidation capacity. Cloud changes offset part of the direct aerosol effects in this model, but only modestly. Hence reductions in these scattering aerosols lead to positive net radiative forcing (warming) as they outweigh the radiative forcing decreases due to declines in the greenhouse gases nitrous oxide and ozone. Qualitatively similar results with aerosol responses greatly outweighing ozone responses were reported previously for land-use changes largely associated with agriculture (Heald and Geddes 2016) and for all nitrogen species changes from preindustrial times to the present day although uncertainties in aerosol forcing are large (Forster *et al.* 2021; Gong *et al.* 2024).

As noted, the aerosol changes would be predominantly driven by changes in emissions from the agricultural sector, which is responsible for around 95 per cent of the reduction in ammonia emissions that dominates aerosol forcing. In contrast, emissions reductions in the industrial sector targeting nitrous oxide would not be expected to drive substantial aerosol changes though they are responsible for about two-thirds of the reductions in nitrogen oxide emissions that dominate the ozone response. Radiative forcing responses in the CESM2 model are consistent with those in the GISS simulations. However, with a single simulation completed in time for this Assessment and the CESM2 model exhibiting larger interannual variability than the GISS-E2.1-G model, their uncertainty range is too large to provide a robust constraint. The forcing under the technical reductions scenario relative to the reference case, for example, is 0.03 (± 0.13) watts per square metre (W/m²) even using an extended 2030–2050 period for analysis.

Though not included in the modelling, which used prescribed methane concentrations from SSP2-4.5, the lifetime of methane would also increase due to the reduced oxidation capacity owing to the reduced nitrogen oxide emissions. In these simulations, methane's lifetime is increased by around 4 per cent under the technical reductions and societal change scenario relative to the reference scenario by 2050. This increase in concentration (burden) relative to SSP2-4.5 (1,789 ppb in 2050) would lead to 0.032 (± 0.005) W/m² additional positive forcing with a slightly smaller value of 0.026 (± 0.004) W/m² for technical reductions scenario relative to the reference scenario. The decrease in nitrous oxide concentrations would also lead to a small increase in methane's lifetime additional to that driven by changes in nitrogen oxide emissions (Forster *et al.* 2021), resulting in additional forcing of 0.006 ± 0.001 and 0.007 ± 0.001 W/m² under the technical reductions and technical reductions and societal change scenarios, respectively. The decrease in methane emissions from livestock due to the nitrogen measures was also evaluated by IIASA. Those decreases in methane emissions represent reductions of 1.8 per cent and 8.0 per cent of total 2040–2050 emissions for the technical reductions and technical reductions and societal change scenarios, respectively.

The respective forcings from these changes are -0.019 (± 0.004) W/m² and -0.088 (± 0.0018) W/m².

Hence accounting for the methane lifetime response to the nitrogen species emissions changes would boost the net positive forcing and hence warming response in these scenarios by around 30–35 per cent. Including reductions in livestock methane emissions in this Assessment's technical reductions scenario would return the forcing to almost what was included in the climate modelling for that scenario. In contrast, including reductions in livestock methane emissions in the technical reductions and societal change scenario would reduce forcing by about 40 per cent, bringing that scenario much closer to the technical reductions case.

Looking out to longer timescales and assuming other factors are constant after 2050, at the levels of the technical reductions and societal change scenario, comparing the technical reductions scenario (SSP1-2.6) with the highest nitrous oxide baseline among the marker SSP scenarios (SSP3-7.0), the nitrous oxide forcing becomes -0.20 (± 0.03) W/m² by 2100, driving the total 2100 radiative forcing to near zero. Turning to very low emission long-term scenarios, those in the *Sixth Assessment Report* of the United Nations Intergovernmental Panel on Climate Change (AR6) database that are consistent with extension of the technical reductions and societal change scenario (Methods in SI 4.1) were examined to extend the technical reductions and societal change scenario. Using the mean of those scenarios (comparable to RCP 1.9 scenarios) relative to the reference case, the 2100 anthropogenic nitrous oxide forcing is -0.24 (± 0.04) W/m². Accounting for the small additional methane lifetime feedback associated with continued nitrous oxide changes after 2050, the net in this case becomes negative in the 2090s even without methane reductions from livestock, whereas it becomes negative around 2070 if those methane reductions are included (Figure 4.1). Hence the near-term increased warming due to nitrogen management measures is likely to be replaced by longer-term reductions in warming although the timing and magnitude of such a transition is dependent upon the assumed reference case, the degree of nitrous oxide reductions achieved, and the timing and magnitude of continued reductions in ammonia emissions after 2050.

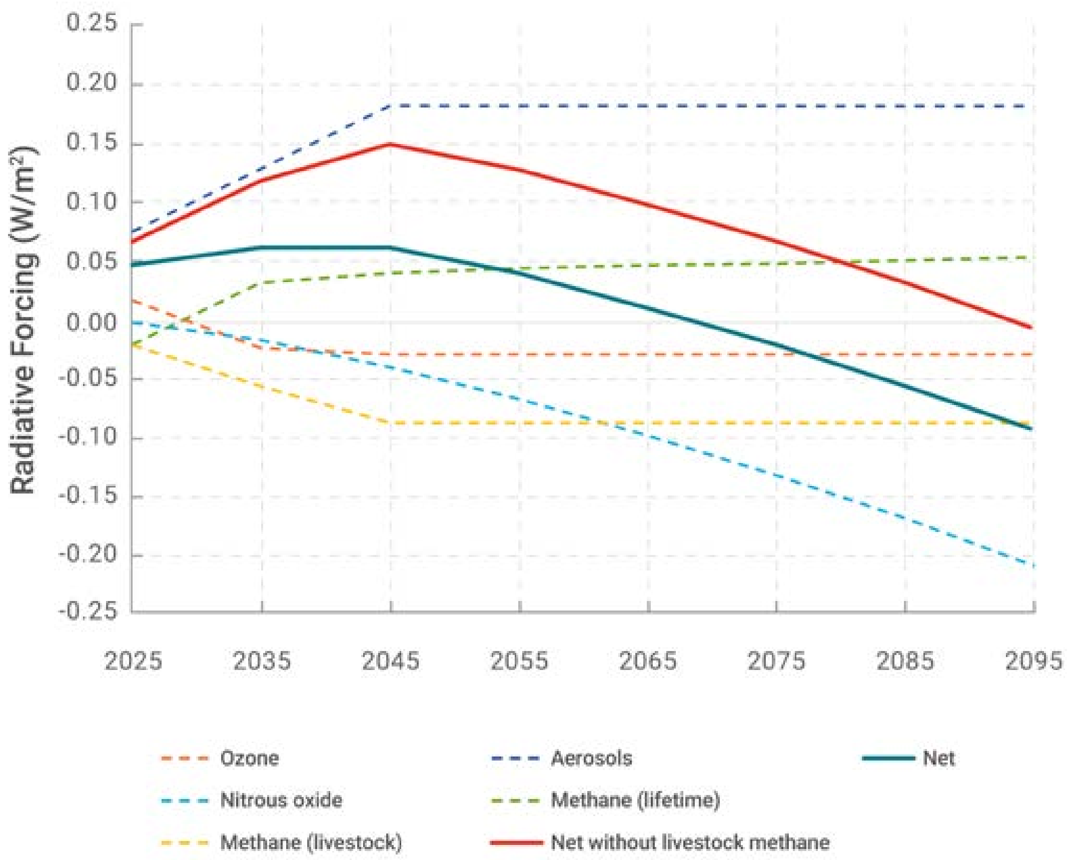


Figure 4.1 Estimated radiative forcing as a function of time by component (dashed) and for the net (solid) under the technical reductions and societal change scenario relative to the reference scenario, 2025–2095, watts per square metre

Note: Values for ozone, aerosols and methane lifetime changes through hydroxyl oxidation are based on decadal means from the climate model simulations through 2050 and constant thereafter. Uncertainties are presented in Table 4.1.

Given previous positive forcing and the time lag between forcing and response, under this Assessment's scenarios net cooling is only likely to be achievable this century if the methane reductions associated with livestock measures are taken into account.

Climate Response

The net positive radiative forcing from those factors included in the model leads to mid-century warming overall, 0.12° (± 0.07°) C for the global mean annual average under the technical reductions and societal change case versus the reference scenario and about half that for the technical reductions scenario versus the reference case (0.06° (± 0.08°) C). Values are higher in the Arctic in both cases, with warmings of 0.46° (± 0.32°) C and 0.67° (± 0.25°) C, respectively. Values are higher in the Arctic in both cases, with warmings of 0.46° (± 0.32°) C and 0.67° (± 0.25°) C, respectively. Values are statistically significant across the ensemble of simulations for much of the northern hemisphere (Figure 4.2).

This result is qualitatively consistent with prior results showing a net warming resulting from reductions in agricultural sector nitrogen oxides and ammonia associated with improved nitrogen use efficiency and technical improvements (Lund *et al.* 2020), though substantially larger. Seasonal changes in precipitation are seldom statistically significant over land areas and changes are generally small. Accounting for the methane lifetime increase in response to the nitrogen species emissions changes would boost these responses by about 25–30 per cent. Including emissions reductions in livestock methane associated with nitrogen measures in that sector on top of the methane lifetime changes would lead to warming in the technical reductions case about 10 per cent greater than that in these simulations. In the technical reductions and societal change scenario, it would reduce the warming to about 55 per cent of that seen in these simulations, bringing those results very close to those reported here for the comparison of technical reductions case as opposed to the reference scenario.

In summary, without considering reductions in livestock methane emissions, in comparison with the reference case, the technical reductions scenario would lead to around 0.08° C of warming by 2050 with a return to about 0° C by 2100, whereas the technical reductions and societal change scenario would cause roughly 0.15° C of warming by 2050 and again a return to about 0° C by 2100 (Figure 4.3). Both scenarios would provide cooling relative to the reference scenario beginning early next century in that case. Including the effects of the methane emissions reductions associated with the decrease in livestock numbers that is required to meet the sustainable nitrogen management goals, both scenarios would lead to about 0.06–0.07° C of warming by 2050 with a cooling approaching 0.1° C by 2100 under the technical reductions and societal change scenario (Figure 4.3).

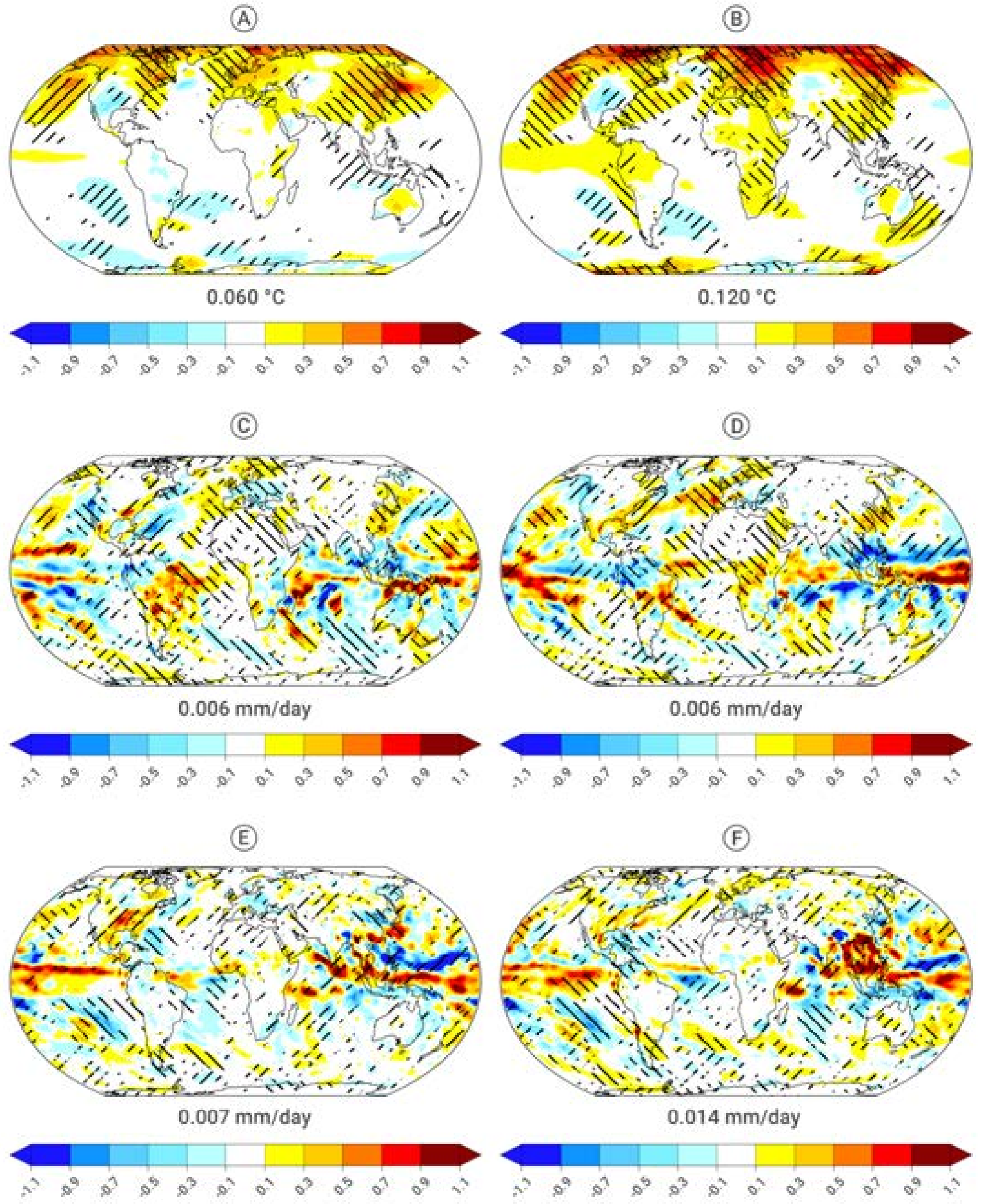


Figure 4.2. Annual average surface temperature and seasonal (December–February C-D, and June-August, E-F) precipitation changes between Technical Reductions Scenario versus the Reference case (A,C and E) and Technical Reductions and Societal Change versus the Reference case (B, D and F) 2040-2050, degrees Celsius and millimetres per day.

Note: Hatching indicates that changes are statistically significant at the 95 per cent confidence interval. Global mean values are presented below each panel.

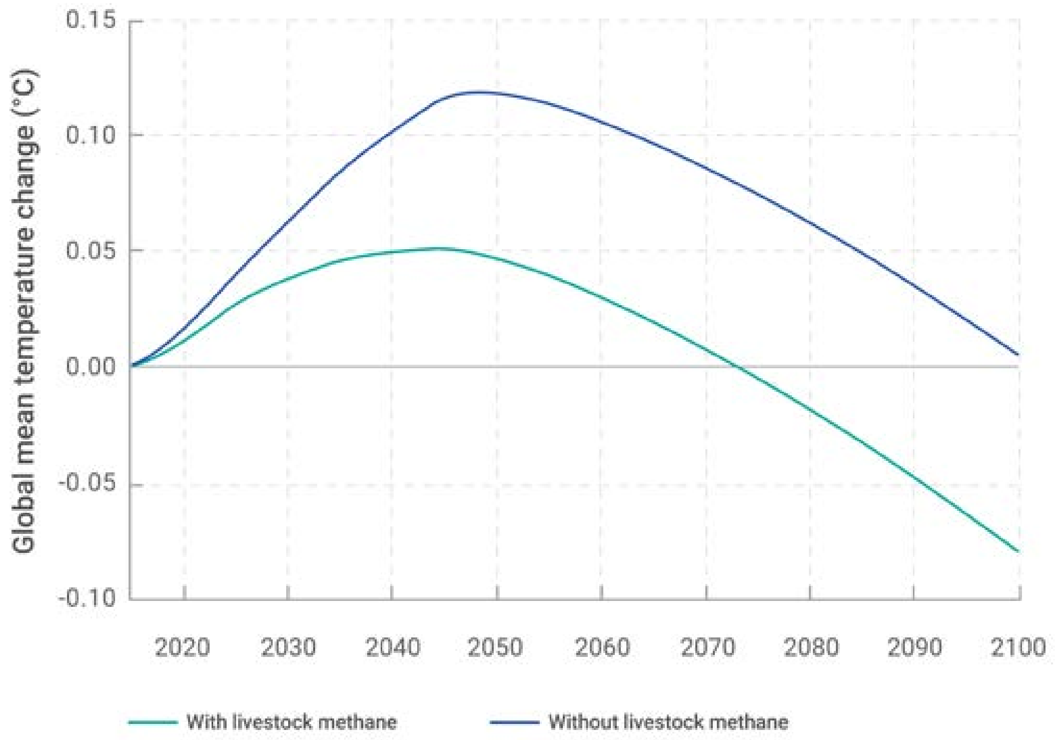


Figure 4.3 Global mean temperature response to the technical reductions and societal change scenario relative to the reference scenario, 2015–2100, degrees Celsius

Note: Estimated using a multi-model mean climate response function (Geoffroy *et al.* 2013) and showing values both incorporating methane emissions changes from livestock associated with nitrogen management and excluding livestock-related methane emissions changes. Uncertainties are ± 0.08° C.

Nitrous oxide reductions as carbon dioxide equivalent emissions

As nitrous oxide is long-lived, changes in nitrous oxide emissions can be readily translated into changes in carbon dioxide-equivalent emissions using the nitrous oxide global warming potential over 100 years (GWP100) of 270 (Forster *et al.* 2021).

In the case of the scenarios examined here, which assume an integrated approach to nitrogen management, ammonia emissions decrease by around 30 per cent in 2050 relative to 2010, which may be much more than in many reference projections. Those decreases would potentially offset much of the benefit of nitrous oxide reductions in terms of avoided carbon dioxide-equivalent emissions. However, in comparison with a situation in which policymakers put in place policies to reduce ammonia, for example, to meet air quality-related commitments such as those under the Gothenburg Protocol, while not reducing, or even increasing, nitrous oxide emissions, the avoided carbon dioxide-equivalent emissions reported here would not be offset by associated ammonia changes but might even be larger.

The nitrous oxide reductions under the technical reductions scenario leads to avoided carbon dioxide-equivalent emissions of 177,000 Mt in comparison with the reference case. The nitrous oxide reductions under the technical reductions and societal change scenario leads to avoided carbon dioxide-equivalent emissions of 235,000 Mt carbon dioxide by 2100 in comparison with the reference case. Even by 2050, when the measures as a whole cause warming, the nitrous oxide reductions will lead to avoided carbon dioxide-equivalent emissions of around 30,000–55,000 Mt CO_2eq/yr. As noted, some of the avoided carbon dioxide-equivalent emissions may be offset by the removal of cooling aerosols depending upon the reference assumptions, particularly the projections of ammonia emissions in the latter part of the century, which are highly uncertain.

4.1.3 Air pollution

Fine particulate matter

As noted in the Introductory Section 4.1.1, reductions in co-emitted ammonia and nitrogen oxides will cause decreases in nitrate and secondary organic aerosols, both of which are components of fine particulate matter ($PM_{2.5}$). The health effects of exposure to fine particulate matter is examined using the Global Exposure Mortality Model (GEMM) risk functions (Burnett *et al.* 2018; see Methods in SI). Under the scenarios used in this Assessment, it was found that technical reductions scenario leads to approximately 400,000–450,000 avoided premature deaths per year by the 2045–2050 period, whereas the technical reductions and societal change scenario leads to about 550,000 avoided premature mortalities per year based on the GISS and CESM model simulations (Table 4.2). These reductions stem primarily from decreases in agricultural ammonia emissions. The results seem qualitatively reasonable given that, for example, this is similar to the fraction attributed to increased ammonia emissions in China associated with changing diets, primarily increased meat consumption) over 1980–2010 (Liu *et al.* 2021). Results using the GEOS-Chem model are similar but larger than those in the GISS and CESM models both for the absolute number of fine particulate matter-attributable deaths and the changes under the scenarios (Table 4.2). The GEOS-Chem results are fairly similar to those reported in a recent study using that model with very similar scenarios and the same exposure-response function for fine particulate matter, though that study did not include changes in meteorology over time (Guo *et al.* 2024). These reductions represent decreases of around 4–9 per cent of the total premature deaths attributable to fine particulate matter as that total is very large averaged over 2045–2050 due to both projected population growth and aging in the SSP2-4.5 scenario (Samir and Lutz 2017; Yang *et al.* 2023; Im *et al.* 2023; Shindell *et al.* 2024).

At the regional scale, benefits are large in many highly populated parts of the world, including and are similar across the models (Figure 4.4). Turning to deaths as a function of time, improved nitrogen management clearly rapidly leads to air quality-related health benefits, with values growing over time and modestly greater benefits under the technical reductions and societal change scenario than the technical reductions case (Figure 4.5). It should be noted that the near-present day health effects of $PM_{2.5}$ exposure based on these models are similar to those in the literature using the same risk functions (Methods in SI 4.1), indicating that the models are credible. Impacts evaluated using the newer GEMM risk function are substantially larger than those obtained using older functions (Burnett *et al.* 2018).

Table 4.2 Fine particulate matter-attributable annual deaths under the scenarios in the models

	Reference	Technical reductions	Technical reductions and societal change
GISS model			
2045–2050 $PM_{2.5}$-attributable annual premature deaths (millions)	10.7 (9.3–12.2)	10.3 (8.9–11.7)	10.2 (8.8–11.6)
Reduction relative to reference case	N/A	410,000 (360,000–490,000)	550,000 (450,000–620,000)
CESM model			
2045-2050 $PM_{2.5}$-attributable annual premature deaths (millions)	10.0 (8.6-11.3)	9.5 (8.2-10.8)	9.4 (8.1-10.7)
Reduction relative to reference case	N/A	440,000 (290,000–580,000)	550,000 (400,000–690,000)
GEOS-Chem model			
2045 $PM_{2.5}$-attributable annual premature deaths (millions)	11.5 (10.0-13.1)	10.9 (9.4–12.4)	10.6 (9.1–12.0)
Reduction relative to reference case	N/A	640,000 (570,000–710,000)	940,000 (830,000–1,050,000)

Note: Ranges shown here are based on uncertainties in the exposure-response function, which dominates the total, and for GISS and CESM these also include modelling of fine particulate matter, with the latter represented by interannual variability in the model simulations. The GEOS-Chem model simulations include projected climate change under SSP2-4.5 from the GISS model.

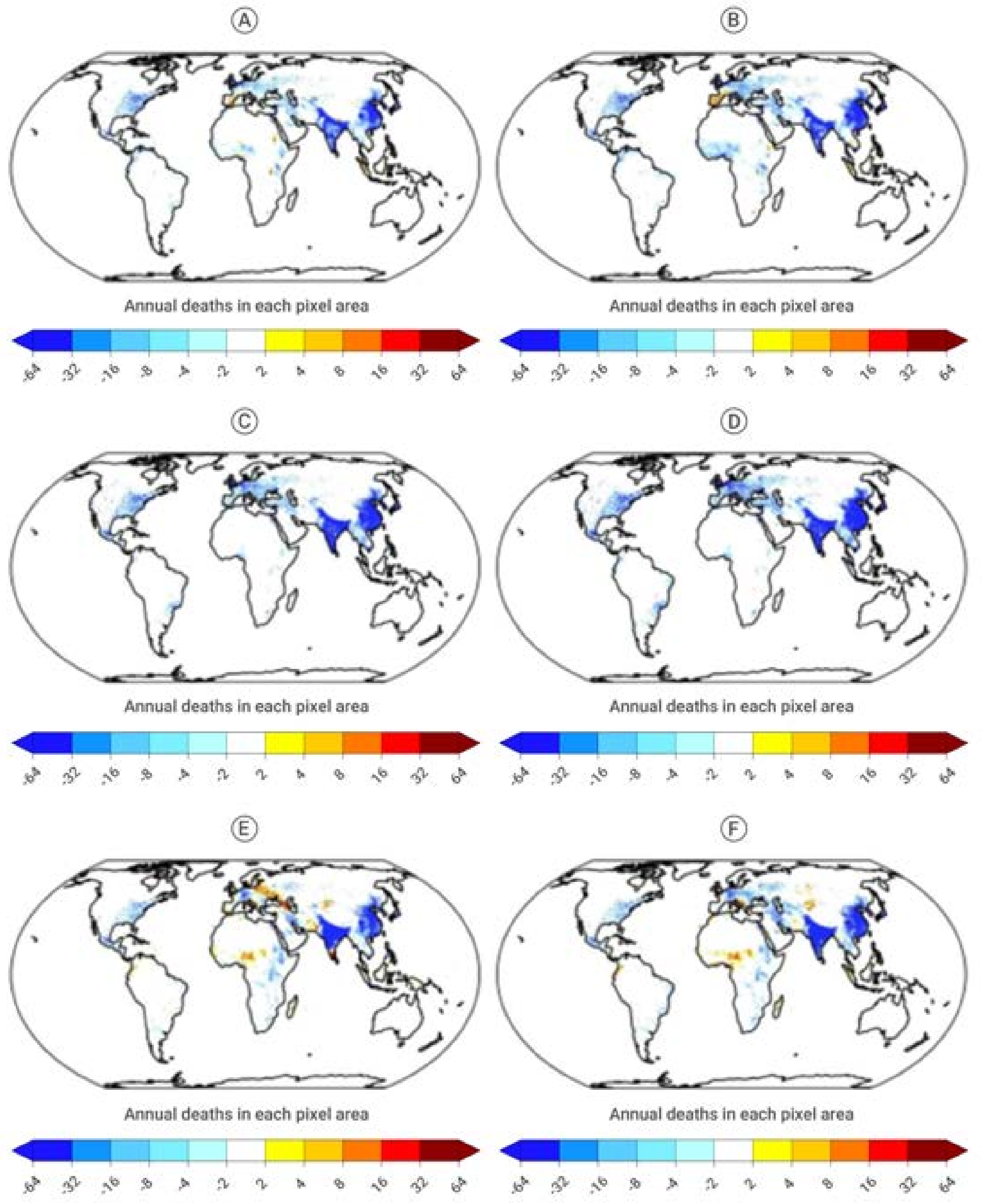


Figure 4.4 Changes in 2045-2050 average fine particulate matter-attributable deaths under the technical reductions (A, C and E) and the technical reductions and societal change (B, D and F) scenarios relative to the reference case in the GISS model (top row) and the CESM model (bottom row) along with the 2045 changes in the GEOS-Chem model (middle row), annual deaths per 0.5° x 0.5° grid box.

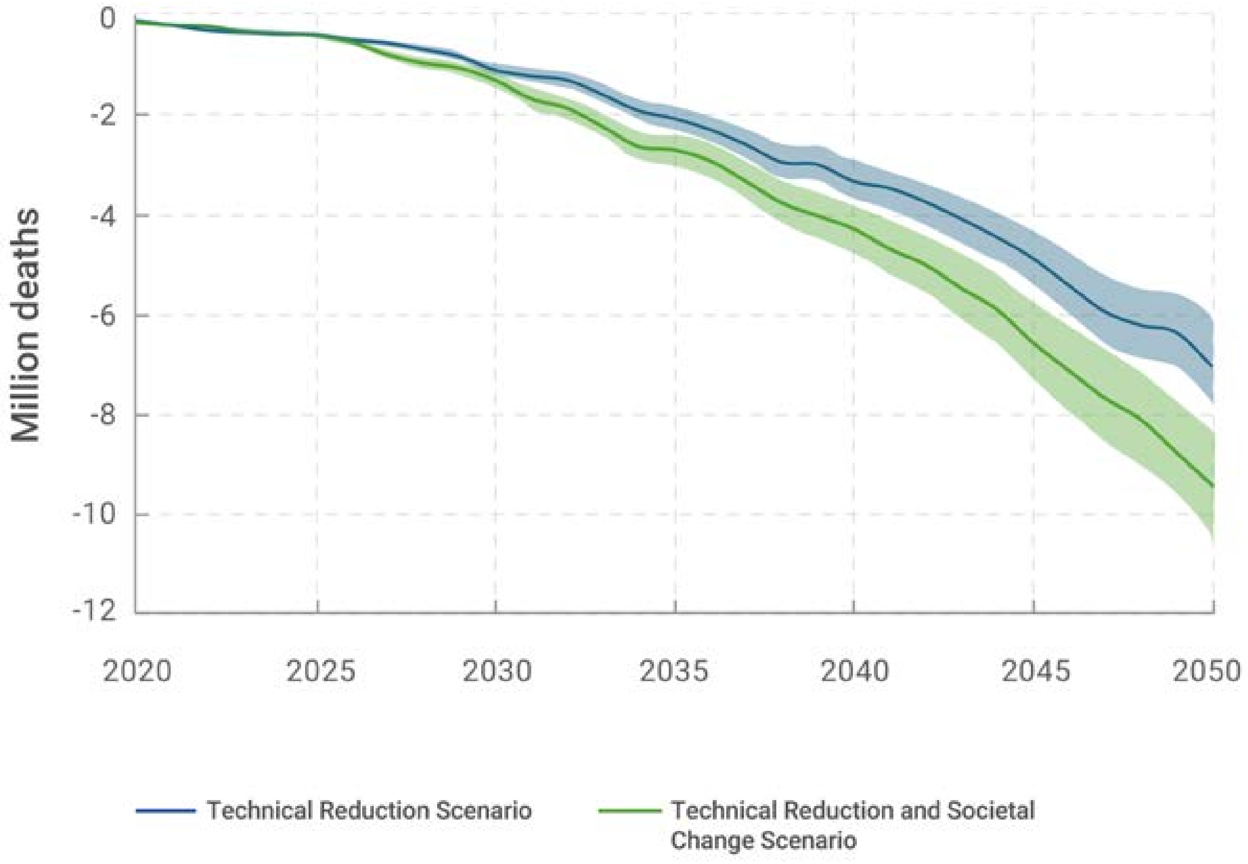


Figure 4.5 Cumulative avoided fine particulate matter-attributable premature deaths under the indicated scenarios relative to the reference scenario based on the GISS model, 2020–2050, million deaths.
Note: Uncertainties are based on uncertainties in the exposure-response function.

Surface ozone

The decrease in tropospheric ozone described in the climate change section of this chapter is similarly present at the surface (Figure 4.6). Ozone decreases are broadly similar across the three models, with the largest reductions in the GISS model and the smallest in CESM, with GEOS-Chem in between at the global scale. Model-to-model differences can be large at the regional scale, however. The large decreases in ozone, for example, over India and Nigeria seen in the GISS and GEOS-Chem models do not occur in the CESM model (Figure 4.6).

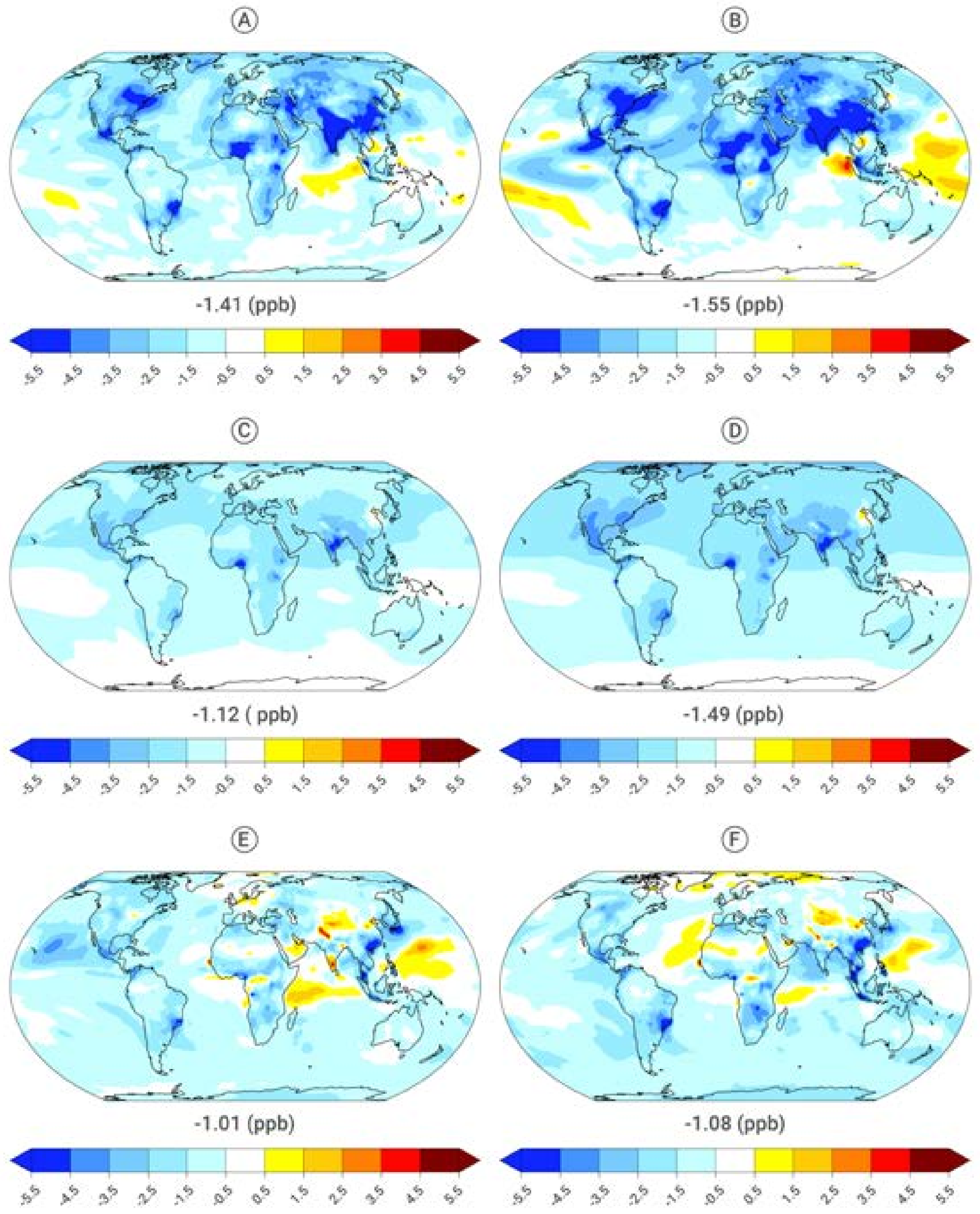


Figure 4.6 Changes in surface ozone (parts per billion by volume) using the annual average maximum daily 8-hour exposure metric simulated in the GISS model (top row), the GEOS-Chem model (middle row), and the CESM model (bottom row) showing the spatial pattern for 2045 under the technical reductions (A, C and E) and technical reductions and societal change (B, D and F) scenarios relative to the reference scenario (bottom)

Note: Global mean values are presented below each panel.

Reductions in ozone are driven by the decreases in emissions of nitrogen oxides in the scenarios and are fairly similar in the two nitrogen mitigation scenarios though, as expected, the decreases are slightly larger under the technical reductions and societal change scenario.

The estimation of ozone-attributable premature deaths is based upon epidemiological analysis using the American Cancer Society Cancer Prevention Study-II cohort, one of the largest studies to date (Turner *et al.* 2016). As with particulate matter, ozone impacts evaluated using this newer risk function are several times larger than those obtained using older functions (Seltzer *et al.* 2018). Although ozone data is not available globally, the GISS model performs reasonably well in comparison with observations over areas with high-quality measurements, although it tends, as in most models, to have a modest high bias (Methods in SI 4.1).

Examining the change in ozone exposure under the scenarios used in this Assessment, it was found that technical reductions scenario leads to approximately 770,000 avoided premature deaths per year by 2045–2050 based on the GISS model, whereas the technical reductions and societal change leads to about 850,000 annually (Table 4.3). Values are roughly half as large based on the CESM model, consistent with its smaller overall response and with a much weaker response in that model over several highly populated regions (Figure 4.6). Total ozone-related premature deaths are predicted to grow substantially by the 2045–2050 period due to both projected population growth and population aging in the SSP2-4.5 scenario, as was the case for fine particulate matter-attributable premature deaths), and these reductions represent decreases of about 20 per cent. Also similar to particulate matter-related deaths, improved nitrogen management clearly leads to rapid ozone-related health benefits, with values growing over time with modestly greater benefits under the technical reductions and societal change than the technical reductions scenario (Figure 4.7). For both fine particulate matter and ozone, air pollution reductions due to decreased emissions of precursors outweigh any climate penalty on air quality due to warming in simulations for this Assessment.

Table 4.3 Ozone-attributable annual mortality under the scenarios in the GISS model.

	Reference	Technical reductions	Technical reductions and societal change
GISS model			
2045–2050 ozone-attributable annual premature deaths (millions)	4.7 (2.8–6.4)	3.9 (2.3–5.4)	3.8 (2.3–5.3)
Difference relative to low-nitrogen regulation case	N/A	770,000 (460,000–1,020,000)	850,000 (510,000–1,130,000)
CESM model			
2045–2050 ozone-attributable annual premature deaths (millions)	4.1 (2.4–5.6)	3.8 (2.2–5.2)	3.7 (2.1–5.1)
Difference relative to low-nitrogen regulation case	N/A	330,000 (180,000–470,000)	390,000 (210,000–550,000)

Note: Ranges shown here are based on uncertainties in the exposure-response function, which dominate the total, and modelling of ozone with the latter represented by interannual variability in the model simulations.

These health impacts of ozone are much larger than those reported in another study using very similar scenarios (Guo *et al.* 2024). The difference is largely attributable to this Assessment's inclusion of multiple causes of death, including cardiovascular diseases and multiple respiratory diseases, whereas the other study included only chronic obstructive pulmonary disease. A smaller portion of the difference stems from the stronger ozone response in the GISS model relative to the GEOS-Chem model, especially over several highly populated areas (Figure 4.6).

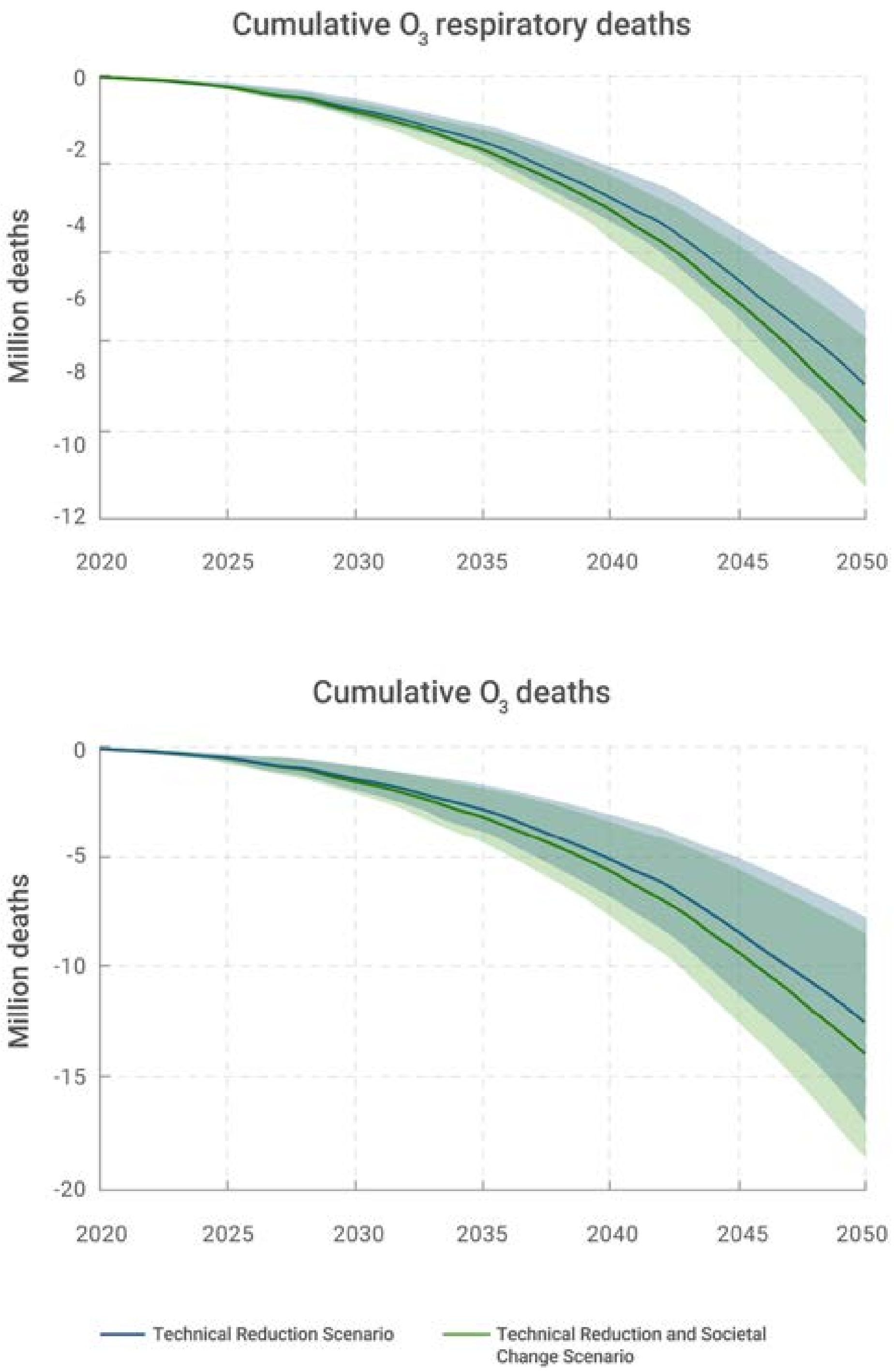


Figure 4.7 Cumulative avoided ozone-attributable premature deaths under the indicated scenarios relative to the reference scenario for (top) respiratory diseases only and (bottom) including the less certain impacts on cardiovascular diseases and diabetes along with respiratory diseases.
Note: Uncertainties are based on uncertainties in the exposure-response function.

Valuation of health impacts

The economic valuation of avoided premature deaths can be examined using standard measures of the value of a statistical life (Methods in SI 4.1). The total air quality-related benefits are estimated to have a valuation of around USD 1.5–2 trillion per year for 2045–2050 based on results of the GISS model. Particulate matter-related valuations would be around 50–70 per cent larger using results from the GEOS-Chem model, and nearly identical using results from the CESM model, whereas the ozone-related valuation would be substantially smaller using the CESM results. Avoided morbidities provide additional benefits.

Table 4.4 Annual values of avoided premature deaths and their valuation (2018 USD) during 2045-2050 based on results from the GISS model.

	Technical reductions *versus* reference scenarios	**Technical reductions *versus* reference scenarios**	**Technical reductions and societal change *versus* reference scenarios**	**Technical reductions and societal change *versus* reference scenarios**
	Particulate matter	Ozone	Particulate matter	Ozone
Avoided mortalities (deaths/yr)	410,000 (360,000–490,000)	770,000 (470,000–1,010,000)	550,000 (450,000–620,000)	850,000 (520,000–1,120,000)
Global value (USD billions/yr)	690 (610–820)	920 (560–1,210)	920 (750–1,040)	1,030 (630–1,360

4.1.4 Carbon cycle and crop-yield changes

The output of the GISS and GEOS-Chem simulations are used to evaluate the effects of the nitrogen scenarios on the terrestrial carbon sink. Surface ozone impacts the growth of vegetation by affecting photosynthesis and stomatal conductance, leading to damage of vegetation and changing the carbon cycle. Atmospheric nitrogen deposition can supply essential nutrients for terrestrial ecosystems by adding nitrogen, which promotes plant growth and sinks, particularly in nitrogen-limited regions. Excessive nitrogen deposition can also have adverse effects on ecosystems, such as causing soil acidification and reducing biodiversity. All simulations show that future improved nitrogen-management scenarios lead to reduced nitrogen deposition and reduced surface ozone. The net impact is an estimated decrease in the global terrestrial carbon sink as reduced ozone concentrations only partially offset the loss of terrestrial carbon sinks caused by reduced nitrogen deposition. Results are similar using GISS or GEOS-Chem simulations of ozone and nitrogen deposition changes, consistent with their fairly similar responses (Figure 6, Figure SI 4.1 and Figure SI 4.2). Results are sensitive to the model used to represent ecosystem responses to ozone exposure (Methods in SI 4.1) and to the specific scenario, but not greatly so.

Reductions in net ecosystem productivity in megatonnes carbon per year are approximately 40 Mt C/yr in 2030, 80 Mt C/yr in 2040 and 110 (±60) Mt C/yr in 2050 averaged across models and scenarios. These differences lead to increases in atmospheric carbon dioxide concentrations of about 0.2 ppm in 2050, which would lead to additional positive radiative forcing of around 0.002 W/m² in 2050, and the same in 2070. nitrogen deposition to ecosystems also leads to modelled decreases in nitrous oxide emissions from terrestrial ecosystems, of about 0.85 Mt N_2O/yr under the technical reductions case and about 1.15 Mt N_2O/yr under the technical reductions and societal change. These would drive additional negative forcings of -0.005 W/m² in 2050. The net effect of these ecosystem responses is small compared with the forcing from ozone or aerosols (Table 4.1) but would provide a very modest climate benefit.

Crop-yield changes were also evaluated (SI 4.1). This initial study did not include the effects of altered nitrogen cycling, The reduced surface ozone exposure leads to increased crop yields, while increased warming generally reduces yields. In the end, the net changes due to these two factors alone are typically small and so are not discussed in detail here, though they can be substantial in some regions.

4.2 NITROUS OXIDE, STRATOSPHERIC OZONE DEPLETION AND ITS IMPACTS

4.2.1 Introduction

The stratospheric ozone layer is critical to protecting life on Earth from harmful ultraviolet (UV) radiation. Manufactured emissions of halogenated chemicals, such as CFCs, have caused substantial stratospheric ozone depletion over the last several decades, putting humans and the ecosystem at risk. The Montreal Protocol, its amendments and adjustments have significantly reduced manufactured emissions of halogenated ozone-depleting substances by implementing production and consumption controls. Even though halogenated ODS can last many decades in the atmosphere once emitted, this action has led to a slow but steadily decrease in the abundance of these chemicals in the atmosphere. Because of the success of this international treaty, global-mean stratospheric ozone levels are expected to return to pre-1980 levels sometime around 2040 (WMO/UNEP 2022) with the Antarctic ozone hole recovering somewhat later.

Photo: JR-50/Adobe Stock

a slow but steadily decrease in the abundance of these chemicals in the atmosphere. Because of the success of this international treaty, global-mean stratospheric ozone levels are expected to return to pre-1980 levels sometime around 2040 (WMO/UNEP 2022) with the Antarctic ozone hole recovering somewhat later.

Nonetheless, unregulated emissions of gases that deplete the ozone layer continue. Nitrous oxide is emitted at the Earth's surface and is transported to the stratosphere, where it depletes the stratospheric ozone layer. Nitrous oxide currently is the most significant ozone-layer depleting substance being emitted to the atmosphere; as its anthropogenic emissions are increasing, and the Montreal Protocol has succeeded in controlling emissions of other long-lived ozone-depleting substances (Figure 4.8). Here, the effect of nitrous oxide on the ozone layer is quantified and it is shown to deplete the ozone layer no matter which greenhouse gas scenario is considered.

In addition to halogenated ODS and nitrous oxide, emissions of carbon dioxide and methane affect the future evolution of the stratospheric ozone layer, through chemical, radiative and dynamic feedbacks (Fleming *et al.* 2011; Portmann *et al.* 2012; Revell *et al.* 2012, Stolarksi *et al.* 2015; Keeble *et al.* 2021). The net effect on the ozone layer, as well as its associated UV radiation and health impacts, is thus strongly dependent on which greenhouse gas pathway is followed (Butler *et al.* 2016). It is thus necessary to investigate how the ozone layer changes under various emission scenarios of carbon dioxide, methane and nitrous oxide. A potentially important, but not typically investigated, scenario is one in which carbon dioxide and methane are mitigated to reach the 1.5–2° C global mean temperature goals set by the Paris Agreement while nitrous oxide emissions continue unabated. Current climate change mitigation strategies have prioritized the reductions of carbon dioxide and methane but not nitrous oxide, despite it being the third most potent greenhouse gas. This Assessment that this scenario results in globally-averaged ozone levels that are lower than pre-ozone depletion historical levels, and they incur additional negative health impacts.

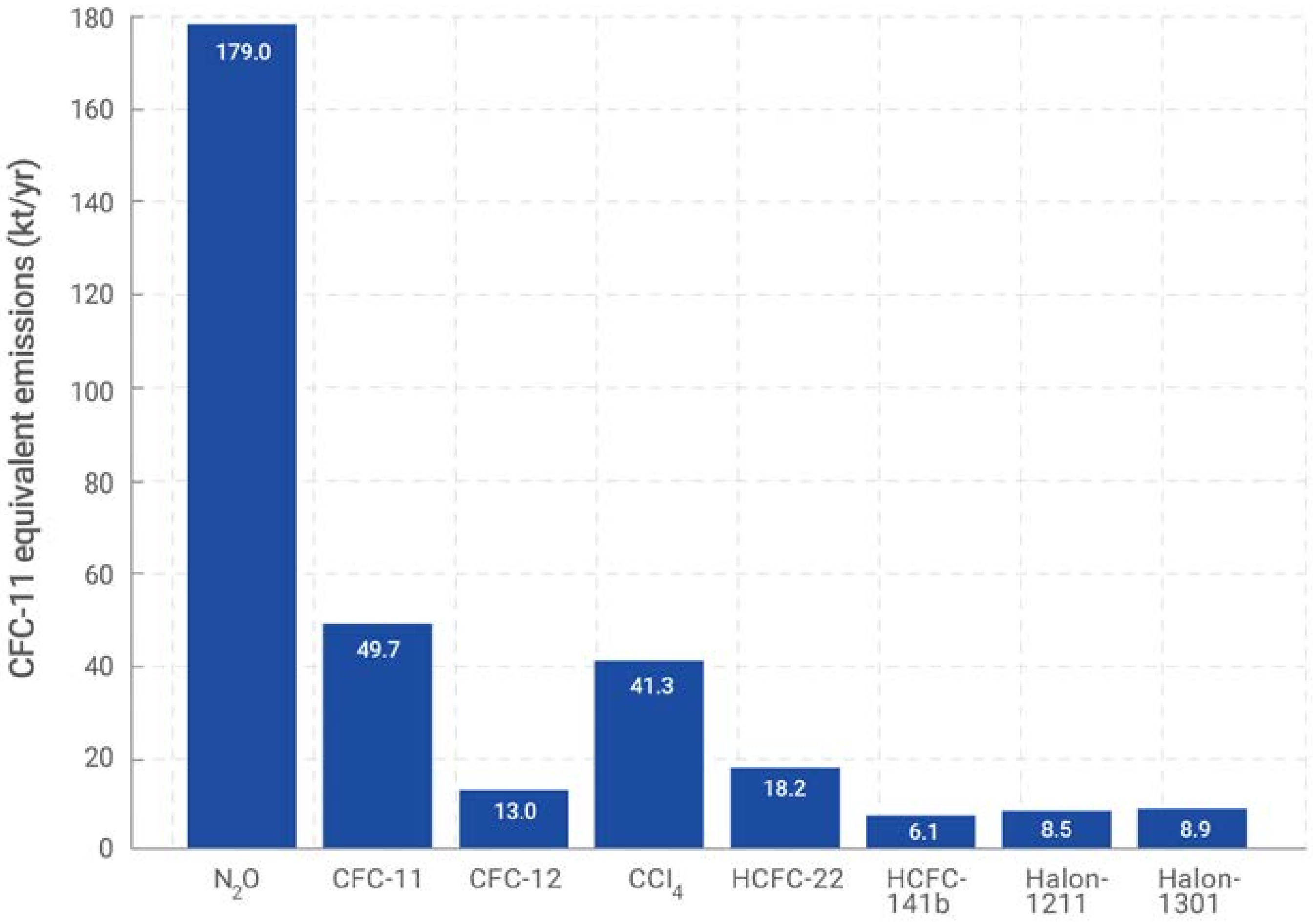


Figure 4.8 Comparison of the ozone-depleting potential-weighted global anthropogenic emissions of nitrous oxide with those of gases controlled under the Montreal Protocol, 2016, in megatonnes of CFC-11 equivalent per year.

Note: It is evident that nitrous oxide is the largest ozone-depleting potential weighted emission, roughly equal to the sum of all other controlled substances. Ozone-depleting substances with a 2019 ozone-depleting potential weighted anthropogenic emission of less than 5 Mt/yr are not shown. CCl_4 = carbon tetrachloride

Photo: Freestockpro/Pexels

4.2.2 Methods

Understanding the future evolution of the ozone layer requires numerical atmospheric modelling that includes time-varying ODS and greenhouse gas abundances, which in combination drive changes in atmospheric circulation, temperature, and chemical composition (Section 4.2.4). In this Assessment, specially designed model simulations are used to examine the interplay between nitrous oxide, methane, and carbon dioxide in determining stratospheric ozone evolution. Two comprehensive chemistry-climate models, CESM version 2 and the Canadian Middle Atmosphere Model (CMAM) and a simpler, but more computationally efficient, two-dimensional model, the National Aeronautics and Space Administration Goddard Space Flight Center two-dimensional model (GSFC2D) were used. The CESM allows testing of the sensitivity of ozone to varying nitrous oxide abundances in a subset of state-of-the-art chemistry-climate models. Due to its low computational cost, the CMAM allows the exploration of a fuller range of emission scenarios. Details of the different models can be found in the Supplementary Information.

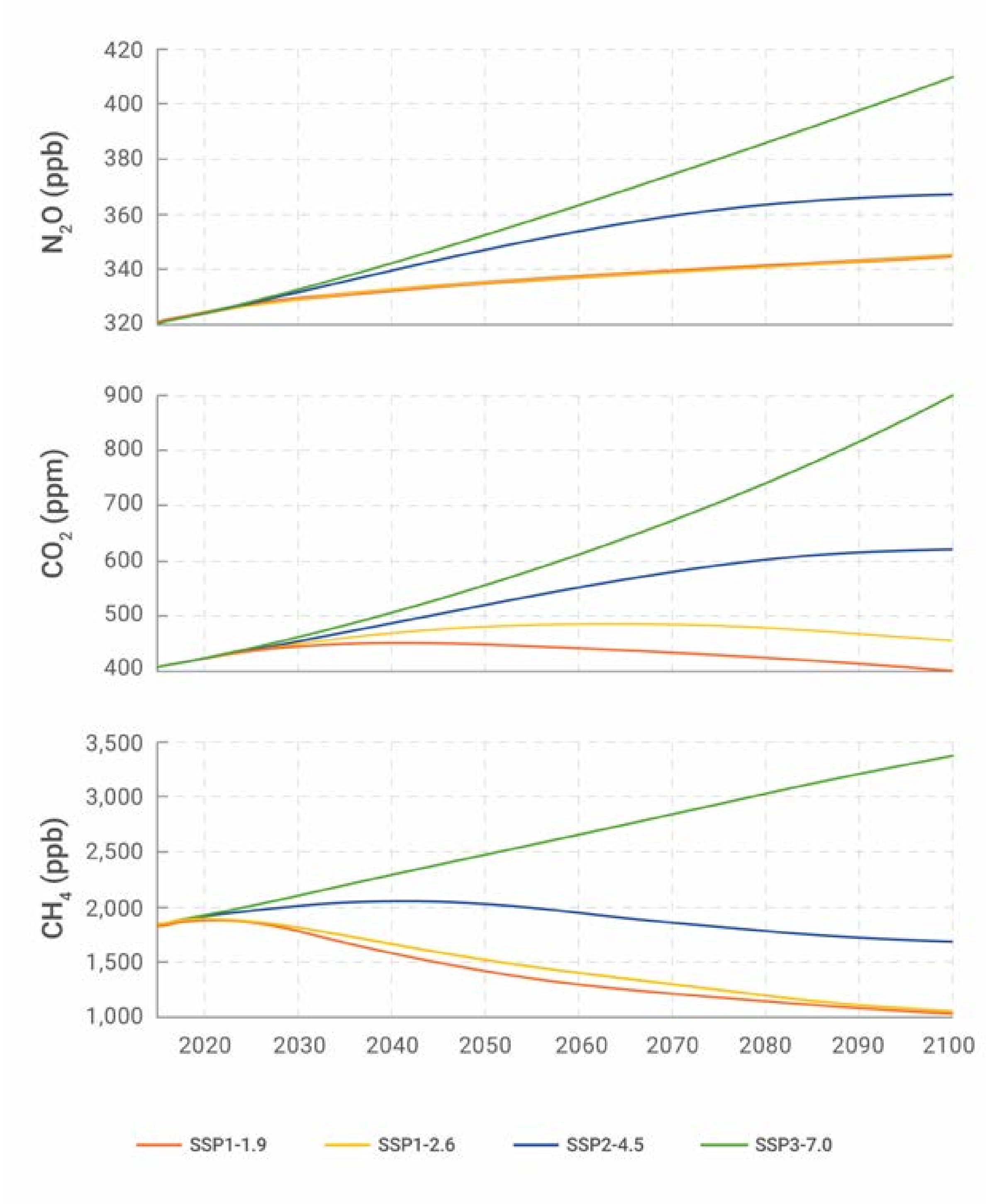


Figure 4.9 Projected global-mean surface concentrations of nitrous oxide (top panel), carbon dioxide (middle panel), and methane (bottom panel) according to the RCP and SSP 2020–2100, parts per billion.

Note: In this assessment scenarios are built using combinations of RCP and SSP scenarios shown in (Table 3.1). This figure shows the trajectories of N_2O, CH_4 and CO_2 that were systematically varied to understand the interaction of N_2O with the ozone layer.

Source: Meinhausen *et al.* 2020

In these simulations, greenhouse gas trajectories are taken from the SSP scenarios (Figure 4.9) (Meinhausen *et al.* 2020). Ozone-depleting substances are assumed to change according to an expectation of adherence to the Montreal Protocol (WMO/UNEP 2022), and do not strongly vary across the SSP scenarios. Even though these are ambitious nitrous oxide mitigation strategies, they only reduce its levels in the atmosphere relative to unmitigated scenarios by a small amount in the next two decades. Even if all its anthropogenic emissions of nitrous oxide were immediately stopped, nitrous oxide concentrations would fall only a few percent by 2040 or even 2050 compared with today's concentration. Critically, this means that the benefits of mitigating nitrous oxide to the ozone layer are much greater by the end of the century than in the near-term. For this reason, the Assessment focuses on changes to the ozone layer at the end of the 21st century. The two SSP scenarios with the largest difference in nitrous oxide at the end of the Century are SSP1-2.6, a high mitigation scenario in which the surface concentrations of nitrous oxide increase by just 25.7 ppb between 2015–2100; and SSP3-7.0, a high emission scenario in which the nitrous oxide surface concentrations increase by 93.6 ppb over the same period.

By systematically varying individual greenhouse gas trajectories shown in Figure 4.9 in model simulations, it is possible to (i) isolate the impact of nitrous oxide on the ozone layer and quantify the magnitude of this effect on the trajectories of other greenhouse gases (Section 4.2.3); (ii) explore the net effect on ozone evolution due to a broad range of possible greenhouse gas trajectories (Section 4.2.4); and (iii) consider a specific scenario to quantify by how much ozone changes if carbon dioxide and methane are abated, i.e., they follow an SSP1-2.6 trajectory, but nitrous oxide emissions are not, i.e., it follows the SSP3-7.0 trajectory. By comparing this simulation with the SSP1-2.6 scenario, the effect of abated nitrous oxide emissions on ozone can be isolated and the associated health impacts quantified (Section 4.2.5).

4.2.3. Nitrous oxide depletes the stratospheric ozone layer

Nitrous oxide in the atmosphere comes from natural and anthropogenic sources (Chapter 2). In this chapter, only the atmospheric effects of anthropogenic nitrous oxide emissions are considered. It is assumed that natural nitrous oxide is in a steady state in the atmosphere since the amount of nitrous oxide abundance does not affect its atmospheric lifetime to a first approximation. Almost half of the nitrous oxide emissions in recent years are anthropogenic in origin (WMO/UNEP 2020; Chapter 2). Even though anthropogenic emissions are now comparable in magnitude to natural emissions, the long atmospheric lifetime of nitrous oxide, roughly 120 years, means a greater fraction of its current atmospheric burden is still natural in origin. Its lengthy atmospheric lifetime also means that it takes a long time for the anthropogenic to reach a steady state, even if such emissions were constant. The abundance of anthropogenic nitrous oxide continues to increase in the atmosphere, with the current growth rates exceeding some of the highest projections (Chapter 2).

Nitrous oxide is an ODS (Ravishankara *et al.* 2009); its ozone-depletion potential (ODP), a metric for the potency of a unit mass emission on ozone relative to that of CFC-11, has been calculated to be 0.017 (Ravishankara *et al.* 2009; WMO/UNEP 2022). Even though this absolute ODP value is small compared to CFCs, for example the ODP of CFC-11, by definition, and that of CFC-12 are both 1, the ODP-weighted emission of anthropogenic nitrous oxide currently is larger than those of any of the ODSs controlled under the Montreal Protocol (Figure 4.8). In addition, the ODP value of nitrous oxide is similar to many of the HCFCs already being phased out under the Montreal Protocol. When expressed as a CFC-11-equivalent, anthropogenic nitrous oxide emissions in 2020 are roughly equal to the sum of all other ODP-weighted emissions from all CFCs in 2019 (WMO 2022) (Figure 4.8); and are equal to more than 10 per cent of the ODP-weighted emissions from CFCs at their peak in 1987.

It has long been known that nitrous oxide emitted at the surface is the primary source of nitrogen oxides, reactive nitrogen oxides (nitric oxide + nitrogen dioxide), in the stratosphere (Crutzen 1970; Crutzen and Enthalt 1977).

The primary chemical pathway by which nitrogen oxides produced from nitrous oxide depletes the ozone layer is to catalyse the removal of ozone through reaction sequences such as:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$O + NO_2 \rightarrow NO + O_2$$

$$\textbf{Net: } O + O_3 \rightarrow 2\,O_2$$

In addition, nitrogen oxides from nitrous oxide also take part in a host of highly coupled processes involving reactive halogen oxides, chlorine oxide (ClO_x) and bromine oxides (BrO_x), from halogenated ODS, or reactive hydrogen oxides, hydrogen oxide (HO_x) = hydroxide (OH) and hydroperoxyl (HO_2) radicals-from water vapor transported to the stratosphere or produced in the stratosphere in situ from the degradation of methane (WMO/UNEP 2022). Nitrogen oxides not only catalyses ozone depletion but also can hinder or enhance ozone depletion from chlorine oxide, bromine oxides and hydrogen oxide (Wennberg *et al.* 1994, 1998; Nevison *et al.* 1999), through several coupled reactions. In the upper troposphere and lowermost stratosphere, the increase in nitrogen oxides can actually enhance local ozone levels by increasing ozone production in a manner analogous to that occurring in a polluted troposphere (Portmann and Solomon 2007; Morgenstern *et al.* 2017), and this effect thus acts to slightly offset the nitrogen oxides catalysed ozone loss in the middle stratosphere above.

Nitrous oxides' effects on ozone have been quantified in previous multi-model comparison studies (Morgenstern *et al.* 2017). Here the methodology, described in the Supplementary Information, is repeated using the three models described above, and for the specific scenario in which carbon dioxide and methane are mitigated and nitrous oxide is not, relative to a scenario in which all three greenhouse gasses are mitigated. The change in total-column ozone (Figure SI 4.1) and vertically resolved ozone (Figure SI 4.4) was calculated relative to the mixing ratio of global-mean surface nitrous oxide. As expected, ozone abundance due to nitrous oxide changes varies with altitude and latitude. It was found that all three models give similar sensitivities of total column ozone to nitrous oxide of around 0.07 Dobson units (DU) decrease in ozone per 1 ppb increase in nitrous oxide in the global-mean (Figure SI 4.1), with larger values at the poles and smaller values in the tropics. The models give better agreement of ozone sensitivity to nitrous oxide for 60º south–60º north latitudes. In the polar regions, larger differences across models are apparent. These differences reflect across-model differences in the vertical and latitudinal ozone response to the imposed scenario (Figure SI 4.4). As expected, most of the ozone is lost in the mid-stratosphere through catalytic cycles.
The ozone production in the lowermost stratosphere is due to the complex chemistry involving hydrocarbons, (especially methane, nitrogen oxides and sunlight.

Note that CCMI-1 used different scenarios to determine the sensitivity of ozone to changes in nitrous oxide from the scenarios used here. That the values in Morgenstern *et al.* (2017) are in relatively good agreement with those found here suggests that the sensitivity of the total column ozone response to nitrous oxide is not highly sensitive to confounding factors such as differences in carbon dioxide and methane (Portmann *et al.* 2012). Additional sensitivity tests in the GSFC 2D model (Table SI 4.2), in which carbon dioxide and methane are also varied, confirm a relatively small influence, about 20 per cent, of the assumed background evolutions of carbon dioxide and methane in the GSFC 2D simulations (Figure SI 4.4). Hence, the magnitude of nitrous oxide's ozone-depleting effect is, to first-order, independent of carbon dioxide and methane concentrations in the atmosphere.

To put the effect of nitrous oxide on global total column ozone changes in context, the calculated ozone depletion avoided due to some of the other currently proposed options for accelerated halogenated ODS mitigation, for example, bank capture, maximises in the mid-21st century and is generally larger than the depletion avoided by nitrous oxide abatement in 2050 (WMO/UNEP 2022). By 2100, however, the ozone depletion avoided by nitrous oxide mitigation in the technical reduction and societal change scenario is larger than the depletion avoided by almost all accelerated halogenated ODS mitigation scenarios.

These results were also compared to the hydrochlorofluorocarbon accelerated phasedown that occurred as a result of amendments to the Montreal Protocol in 2007. The GSFC 2D model was used to perform

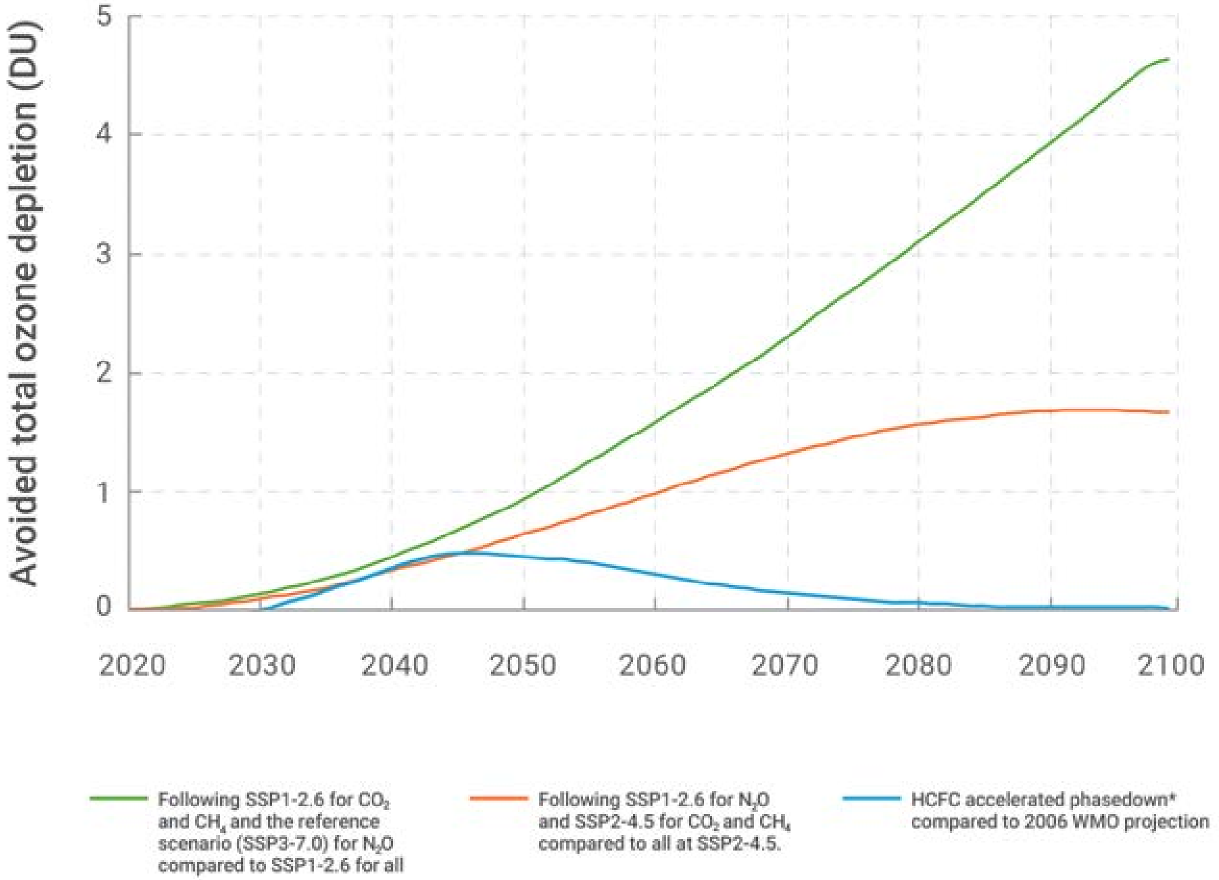


Figure 4.10 Difference in globally averaged total column ozone, 2020-2100, following: (green line) SSP1-RCP 2.6 for carbon dioxide and methane and the reference scenario (SSP3-7.0) for nitrous oxide, compared to SSP1-RCP 2.6 for all; (orange line) SSP1-RCP 2.6 for nitrous oxide and SSP2-RCP 4.5 for carbon dioixde and methane, compared to all at SSP2-RCP 4.5; and (blue line) HCFC accelerated phasedown, using the (*) chlorodifluoromethane projection from the 2010 World Meteorologic Organization Ozone Assessment with accelerated phasedown minus the hydrochlorofluorocarbon projection from the 2006 World Meteorologic Organization Ozone Assessment, Dobson units.

Note: The hydrochlorofluorocarbon curve is slightly below zero in the early years due primarily to higher reported production and increased annual bank release rates in the 2010 Assessment relative to the 2006 Assessment.
Source: GSFC 2D model

sensitivity experiments in which a SSP2-4.5 scenario was compared for a case in which chlorodifluoromethane (HCFC-22) follows either future projections assumed in the 2006 World Meteorologic Organization (WMO) Ozone Assessment (WMO 2007) or those given by the 2010 WMO ozone assessment report (WMO 2011), which included the accelerated phasedown (Figure 4.10;Table SI 4.2). When the integrated effects are compared, the nitrous oxide abatement between the SSP2-4.5 and SSP1-1.9 scenario is roughly equivalent to the hydrochlorofluorocarbon accelerated phasedown benefit over the next two decades and five times the benefit when averaged over 2020–2100. Nitrous oxide abatement between the SSP3-7.0 and SSP1-1.9 scenarios gives a larger integrated effect than the hydrochlorofluorocarbon accelerated phasedown benefit over the next two decades, and 12 times the benefit over 2020–2100.

4.2.4 Net effects on global ozone depend on the greenhouse gas scenario

The net changes to global ozone in the future are highly sensitive to the combined influence of concentrations of greenhouse gasses, such as nitrous oxide, carbon dioxide and methane, and halogenated ozone-depleting substances, for example, chlorofluorocarbons. As discussed in Section 4.2.3, increasing anthropogenic nitrous oxide by itself depletes ozone; this effect accumulates over time, so that in a medium emissions scenario by the end of the 21st century, nitrous oxide's depleting effect on globally-averaged ozone is greater than that of halogenated ODSs (Figure 4.11).

On the other hand, increasing carbon dioxide and methane tend to increase globally-averaged column ozone through a variety of complex processes. Increasing carbon dioxide cools the stratosphere, which slows chemical ozone loss cycles (Haigh and Pyle 1982). Increasing carbon dioxide is also predicted to enhance tropical upwelling and large-scale stratospheric circulation

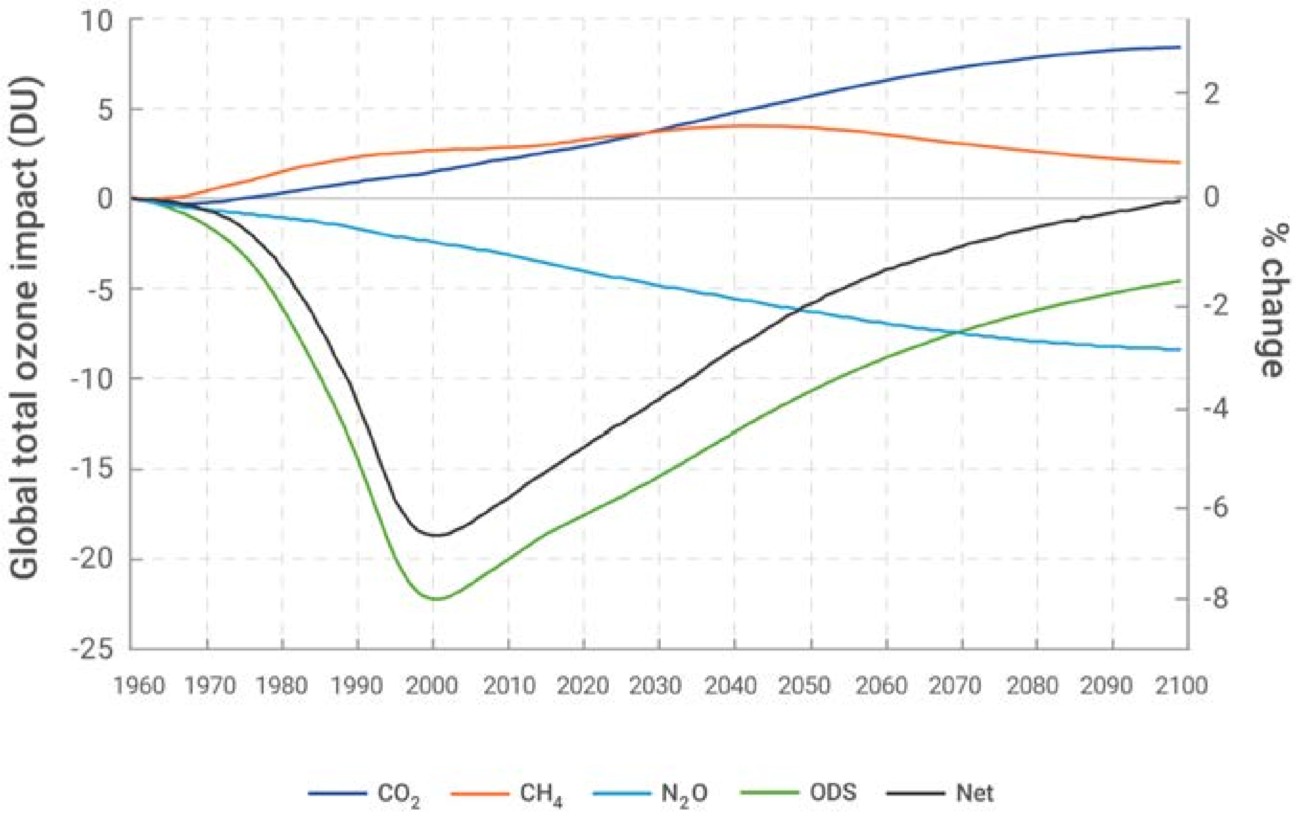


Figure 4.11 Changes in global-average total column ozone due to the separate impacts of time-varying carbon dioxide, methane, nitrous oxides and long-lived halogenated ozone depleting substance, 1960–2100, Dobson units, DU, (the thickness, in millicentimeters, of the entire column ozone if it were all brought to the pressure at Earth's surface) and per cent relative to 1960

Note: Each gas is varied individually while the other gasses are fixed at 1960 levels, and the net impact of all gasses combined is also shown as the black line. Historical global surface concentrations are used for 1960–present for the greenhouse gases (Meinshausen *et al*. 2020) and ODS (WMO/UNEP 2022); future concentrations are from SSP2-4.5 greenhouse gas and A1 (Baseline) ODS scenarios.
Source: GSFC 2D model.

(Brewer-Dobson) (Hardimann *et al.* 2014), which transports nitrous oxide as well as redistributes stratospheric ozone and trace gasses. Methane affects stratospheric ozone mainly through its role as a chemical agent, impacting chlorine partitioning, water vapour production and nitrogen oxide chemistry. In particular, increasing methane by itself tends to increase globally-averaged ozone primarily through enhanced upper tropospheric and lower stratospheric ozone production and the reduction of the chemical chain-length of the chlorine catalytic cycles in the stratosphere (Revell *et al.* 2012). Increased concentrations of halogenated ODS caused by large past emissions, prior to the controls implemented by the Montreal Protocol and its subsequent adjustments and amendments, drove large ozone losses in the late 20th and early 21st century, but their influence will weaken by the end of the 21st century, though their concentrations will still be higher than their 1960s levels.

The net effect on ozone due to individual greenhouse gasses and ODS in Figure 4.11 is for one particular middle-of-the-road emissions scenario. By systematically varying the trajectories of carbon dioxide, methane and nitrous oxide it is evident that a broad range of outcomes for ozone levels at the end of the 21st century is possible, depending on which trajectory for each gas is followed (Figure SI 4.5). In particular, strong carbon dioxide and methane abatement, for example, low emissions, scenarios result in globally-averaged total column ozone still slightly below 1980 levels by the end of the 21st century; while little-to-no abatement scenarios, for example, high emissions, show ozone recovery, sometimes to levels well above those in 1980, by the end of the century (Keeble *et al.* 2021). This is because high greenhouse gas emissions leads to accelerated ozone recovery through carbon dioxide-induced stratospheric cooling, which impacts chemical reaction rates and increases mid-to-upper stratospheric ozone, and through the acceleration of the large-scale stratospheric circulation, which transports ozone from its tropical photochemical production region to higher latitudes where ozone lifetime is longer. In addition, increased methane acts to enhance photochemical ozone production in the upper troposphere and lower stratosphere, further accelerating ozone recovery. In contrast, the slower ozone recovery in the low greenhouse gas emissions scenarios occurs because the reduction in carbon dioxide and methane emissions slows these same processes. An additional driver of the long-term ozone evolution in these scenarios is decreases in tropospheric ozone precursor emissions (WMO/UNEP 2022).

4.2.5 Changes in ozone and associated health impacts for a scenario in which carbon dioxide and methane are abated but nitrous oxide is not

Changes in ozone

As discussed in Section 4.2.4, abating carbon dioxide and methane will lead to a slower recovery of globally-averaged ozone. Only in a strong carbon dioxide and methane abatement scenario such as SSP1-2.6 do ozone levels across all latitudes remain lower relative to historical levels (1960–1970) even at the end of the 21st century (2090–2100) (Figure SI 4.5; Figure 4.12). In the tropics and subtropics, ozone levels remain lower even than levels simulated during the decade of peak ozone depletion (1995–2005) (Figure 4.12). In southern hemisphere high latitudes, ozone levels are higher than during peak ozone depletion, but still less than pre-ozone-depletion historical levels. This scenario (SSP1-2.6) assumes that nitrous oxide is also abated. In the event that carbon dioxide and methane are mitigated but nitrous oxide is not, additional global-mean total column ozone losses of up to -5 DU by the end of the 21st century occur from increases in nitrous oxide alone (Figure SI 4.6; Figure 4.12). These additional ozone losses due to nitrous oxide are similar in all three models (Figure SI 4.6) and are consistent with previous studies, despite differences in the underlying scenarios (Portmann *et al.* 2012, Butler *et al.* 2016, Morgenstern *et al.* 2017).

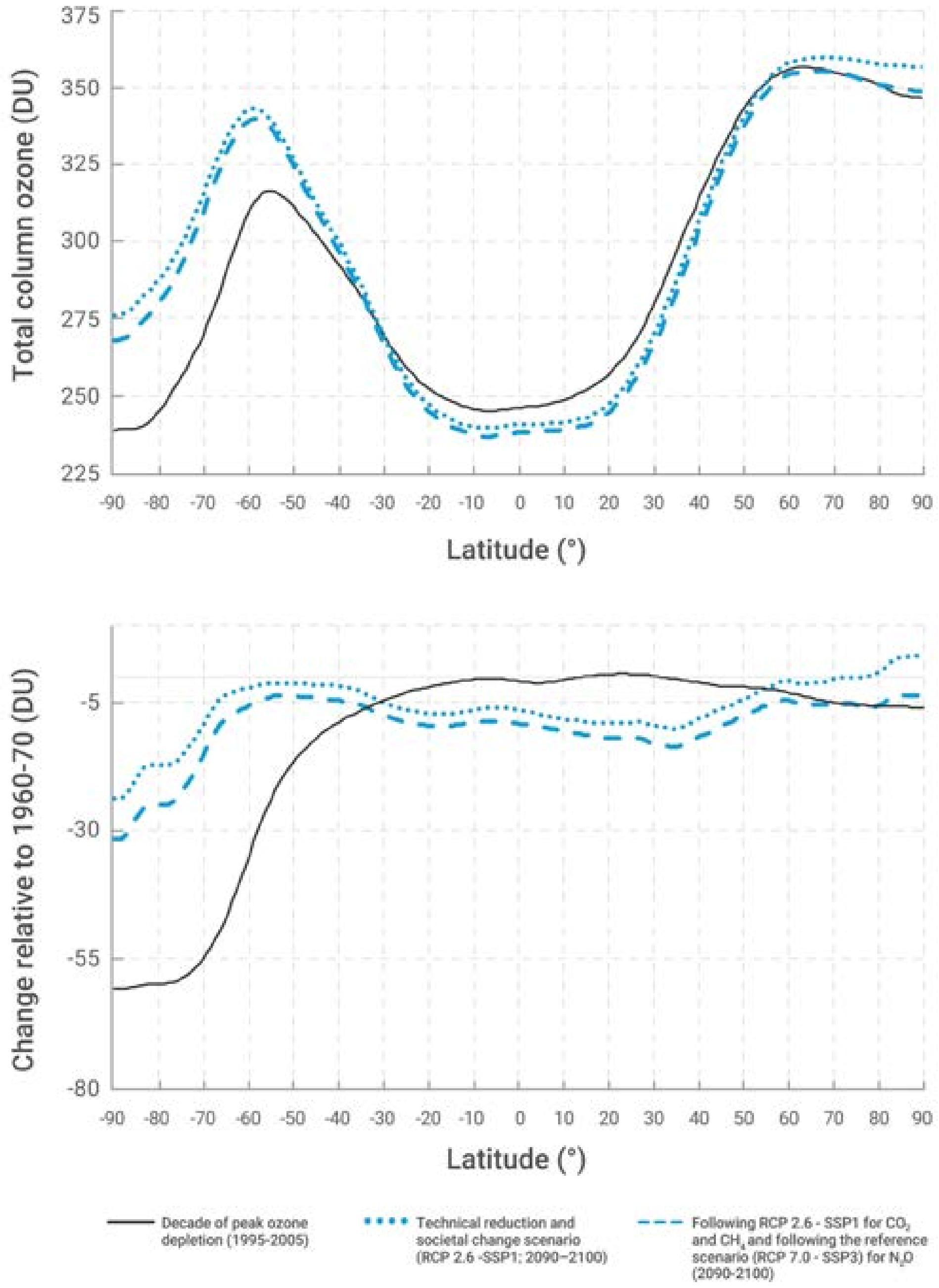


Figure 4.12 (Top) total column global ozone in Dobson units, DU, simulated using Whole Atmosphere Community Climate Model for (black line) the decade of peak ozone depletion (1995–2005), (dotted line) the end of the 21st century following the technical reduction and societal change scenario (RCP 2.6 -SSP1-2.6; 2090–2100), and (dashed line) the end of the 21st century following RCP 2.6 - SSP 1-2.6 for carbon dioxide and methane but following the reference scenario (RCP 7.0 - SSP3-7.0) for nitrous oxide. (Bottom) the change in ozone in Dobson units for the same periods/scenarios as in the left panel, but relative to the pre-ozone-depletion period (1960–1970)

Note: The lines are averages of three ensemble members.

Photo: Vinicius Maciel /Pexels

Changes in ultraviolet and associated health impacts

Using the column ozone changes for a given scenario, the changes in the amount of UV radiation that is biologically active in terms of its ability to induce skin cancer. Biologically active UV radiation, E_{bio}, can be determined. E_{bio} depends on solar zenith angles, i.e., on latitude, season and time of day; total ozone column; aerosols; surface albedo and clouds. Here monthly-mean E_{bio} values summed over each year to obtain annual UV exposures for health effect estimates are used. Details of estimating E_{bio} can be found in the Supplementary Information. For ease of presentation, five latitudinal belts are considered:
(i) northern high latitudes (60–90° N),
(ii) northern mid-latitudes (30–60° N),
(iii) equatorial latitudes (30° S–30° N),
(iiii) southern mid-latitudes (30–60° S),
and (v) southern mid-latitudes (60–90° S).

The UV differences between the SSP1-2.6 with nitrous oxide from SSP3-7.0 scenario relative to the SSP1-2.6 scenario for the period 2020–2100 are displayed in Figure SI 4.7 and are summarised in Table 4.5 as decadal averages. Relative to the scenario in which all three greenhouse gasses are abated (SSP1-2.6), skin cancer- and cataract-inducing UV radiation increases in all latitude bands by the end of the 21st century in the scenario in which nitrous oxide is not abated.

Table 4.5 Percentage difference in annual skin cancer-inducing UV radiation, for the SSP1-2.6 with nitrous oxide from the SSP3-RCP 7.0 scenario relative to the SSP1-RCP 2.6 scenario for the period 2020-2100, for five different latitude bands. Average of the 2D, Canadian Middle Atmosphere and Whole Atmosphere Community Climate models for decades centred on the given years

Year	90° S–60° S	60° S–30° S	30° S–30° N	30° N–60° N	60° N–90° N
2025	2.4	0.2	-0.1	0.0	-0.1
2035	1.0	0.3	0.0	0.1	-0.1
2045	2.2	0.6	0.1	0.0	0.0
2055	2.1	0.8	0.3	0.4	0.4
2065	2.4	0.9	0.6	0.4	0.3
2075	2.7	1.2	0.8	1.0	1.0
2085	3.9	1.7	1.0	1.0	0.9
2095	3.3	1.7	1.3	1.7	1.9

The greatest increase of up to 3.9 per cent is projected for the southern high latitudes near the end of the 21st century, while for other latitude bands the increases are smaller ranging between 1.3 and 1.9 per cent. These increases due to unmitigated nitrous oxide will add to the expected increases in UV radiation in the tropics and northern mid-latitudes that occur primarily due to reduced carbon dioxide and methane (Yamamoto *et al.* 2024), and will partly compensate for the decreases in UV radiation at southern mid-latitudes that are projected for the end of the century in the SSP1-2.6 scenario relative to 1995-2005.

The changes in annual UV irradiances can be used to estimate the consequent health effects. The UV-dependent adverse health effects considered here are the induction of skin cancers –melanoma, basal, and squamous – and cataracts. Cutaneous malignant melanoma is an aggressive cancer with more than 325,000 new cases and 57,000 mortalities worldwide in 2020 (Arnold *et al.* 2022; Neale *et al.* 2023). About 6.4 million new cases of basal cell and squamous cell skin cancers, with 56,000 fatalities, were estimated for 2019 (Zhang *et al.* 2021; Neale *et al.* 2023). Cataracts are a leading cause of blindness globally and resulted in an estimated loss of 6.7 million disability-adjusted life years (DALYs) in 2019 (Löfgren 2017; Neale *et al.* 2023). Using estimates for the ozone layer depletion for any scenario, such health impacts can be calculated for the respective conditions (Figure 4.13; Table SI 4.3). These changes depend on latitude and thus may impact countries differently, depending on their location, population and genetic susceptibilities, for example, skin or eye colour, for which data are scarce. Notably these estimates do not consider any changes in the actual exposure of humans to solar UV radiation due to occupational- or recreational-life patterns and atmospheric variability due to climate change.

The key finding is that if methane and carbon dioxide are mitigated according to SSP1-2.6 and nitrous oxide is not, there will be appreciable increases in health impacts, reaching around 4 per cent in squamous cell carcinoma at southern midlatitudes and about 2.5 per cent in the tropics and northern mid-latitudes. For the other skin cancers and cataracts, the risks are milder but the absolute numbers greater. The percent changes presented here should be taken as broad guidance rather than specific predictions, but even with this limitation any increase in the already large incidence rates of skin cancer and cataracts is of concern to public health.

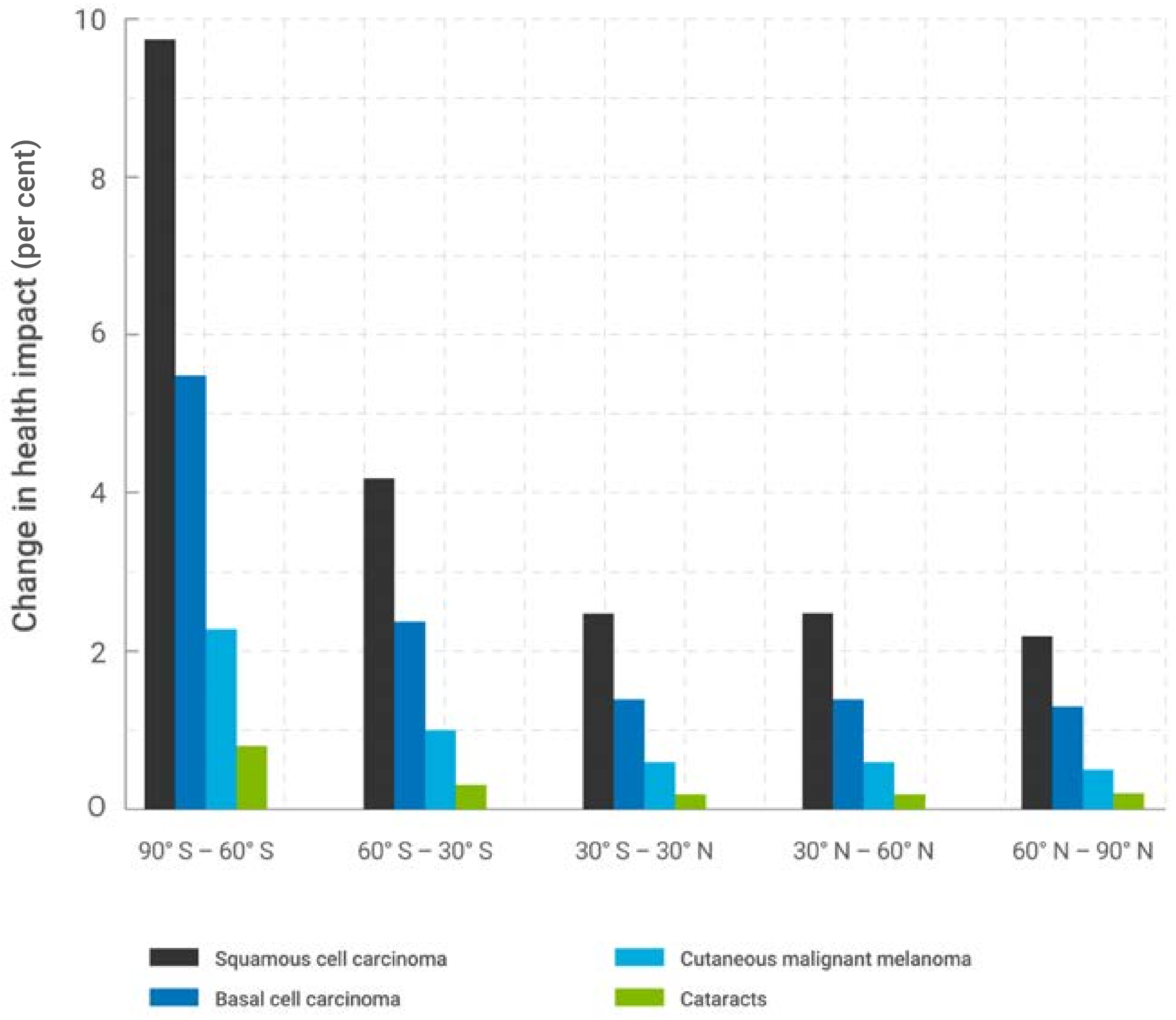
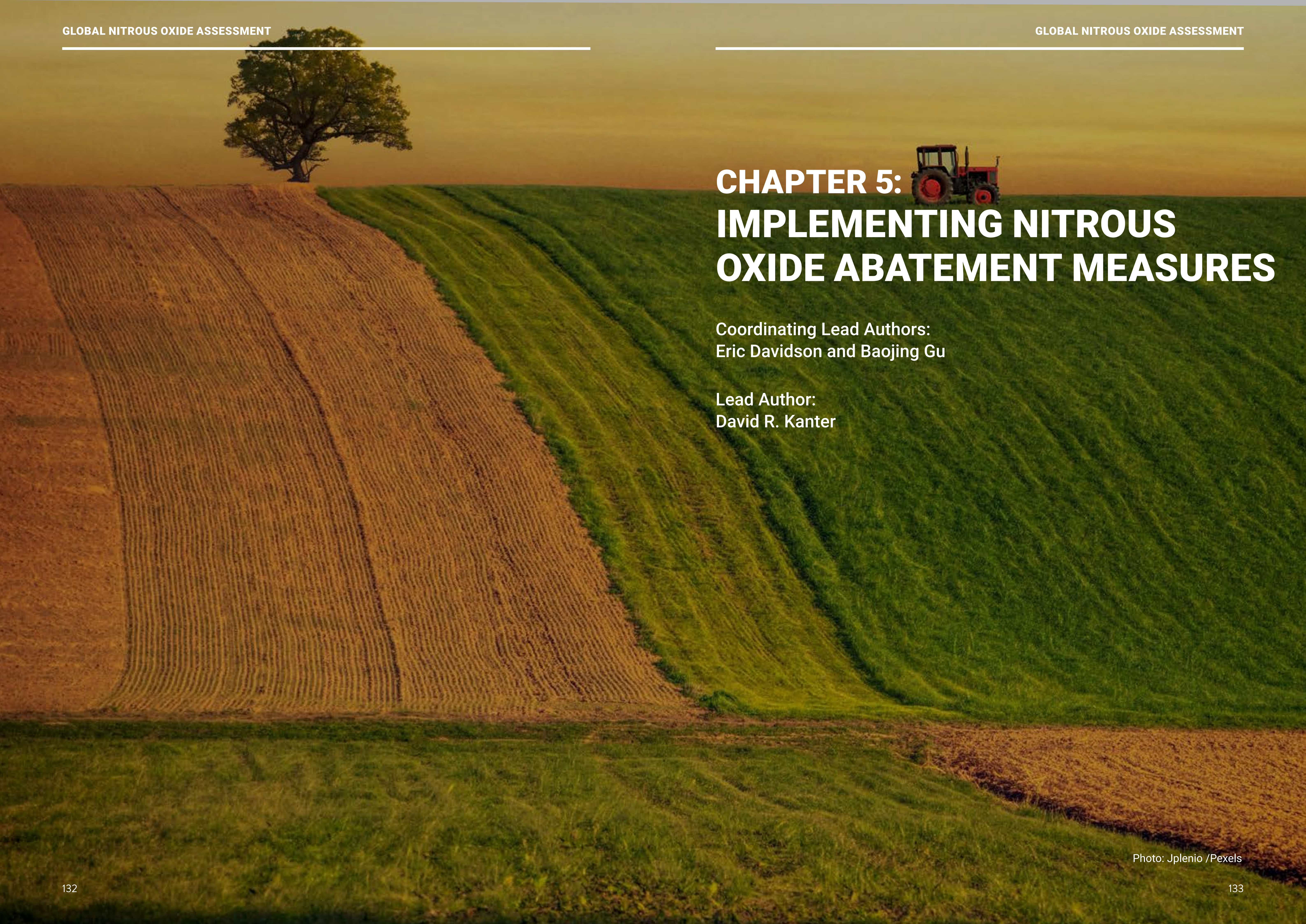


Figure 4.13 Percent difference in health impacts due to changes in ultraviolet radiation for the centred year of 2080–2090 (Table 4.5, for the technical reduction and societal change (SSP 1-RCP 2.6) scenario with nitrous oxide from (SSP 3-RCP 7.0) scenario relative to the technical reduction and societal change (SSP 1-RCP 2.6) scenario, for five different latitude bands

Note: These estimates do not include many factors, such as future changes in cloud cover and aerosols, occupational and recreational exposure patterns, demographic shift, or disease latency.



CHAPTER 5:

IMPLEMENTING NITROUS OXIDE ABATEMENT MEASURES

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KEY MESSAGES

1. Nitrous oxide emissions from adipic acid and nitric acid production industries could be nearly eliminated by adoption of existing and relatively low-cost abatement measures (USD 1,600–6,000 per tonne of nitrous oxide; USD 6–22 per tonne of carbon dioxide equivalent). It is low-hanging fruit for near-term abatement and even though it currently represents approximately 5 per cent of anthropogenic emissions, this could increase in the future.

2. Abatement potentials of up to 50 per cent by 2050 have been estimated for the significant emissions from agriculture, including croplands, grasslands and manure management, but the estimated costs are variable, uncertain and generally high (USD 6,300–49,000 per tonne of nitrous oxide; USD 23–180 per tonne of carbon dioxide equivalent). These measures include a variety of improved nutrient management options and dietary changes. Realising these potentials will likely require significant investment to promote adoption of innovative practices and behaviour.

3. Published estimates of the social costs of nitrous oxide fall in a similar range as abatement costs: from USD 1,000–4,600 per tonne of nitrous oxide for stratospheric ozone damage, and USD 25,000–60,000 per tonne of nitrous oxide for climate damage.

4. Anthropogenic emissions from other sectors, such as energy production, transport, aquaculture and wastewater management, could be abated as co-benefits of decarbonisation and other optimisation efforts related to those sectors.

5. Deeper emissions reductions will require further innovation and re-imagining of how food production systems utilise nitrogen in more targeted, efficient and circular systems.

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5.1 INTRODUCTION

This Assessment projects that emissions in 2050 could be abated by about 22 per cent relative to 2020 under the technical reductions scenario and 44 per cent under the technical reductions and societal change scenario (Table 3.2).

Compared to a reference case of projected 2050 emissions, the abatement by 2050 could be about 40 per cent and 56 per cent for the same two scenarios, respectively. This chapter discusses the potential costs of those abatement measures, and they could be implemented.

Photo: Yellow Boat / Adobe Stock

5.2 INDUSTRY

5.2.1 The potential for abatement

Nitric acid production, which is needed to make synthetic nitrogen fertilisers, munitions and adipic acid, emits nitrous oxide as an unintended byproduct. Production of adipic acid and caprolactum, which are used to make nylon and other products, also emits nitrous oxide as an unintended byproduct – caprolactum production is only a minor contributor to nitrous oxide emissions. Affordable technologies currently exist to nearly eliminate nitrous oxide emissions from these industrial processes (Davidson and Winiwarter 2023). For both adipic and nitric acid plants, thermal destruction or a variety of catalytic processes can be used to abate nitrous oxide emissions by 90–99 per cent. Of the approximately 500 nitric acid production plants worldwide, about 100 currently abate nitrous oxide emissions, while about half of the 21 adipic acid plants currently abate them. The technical reductions scenario projection in this Assessment assumes that emissions from nitric acid and adipic acid production will be fully abated in all Organisation of OECD countries by 2050 and in other countries by 2070 (Table 3.3), resulting in near-zero emissions by 2050 (Table 3.2).

The largest success to date in reducing emissions from adipic and nitric acid plants has occurred in the European Union (EU), in which its emissions trading scheme (ETS) was used to fund installation of abatement technologies in nearly all plants (Davidson and Winiwarter 2023).

This success is being exported through foreign assistance of the German government's Nitric Acid Climate Action Group. That programme has procured statements of understanding with numerous low-income and middle-income countries to help finance and install nitrous oxide abatement technology in their nitric acid plants. In the United States (US) about half the nitric acid plants have nitrous oxide abatement as a co-benefit of regulated nitrogen oxides abatement in regions of the country in which air quality standards for nitrogen dioxide and ozone cannot be met. The nitric acid plants in regions of the US that currently meet air quality standards are not required to abate either nitrogen oxides or nitrous oxide emissions, and thus would need other incentives or new regulations for abatement.

One of two US adipic acid plants has abated about 95 per cent of its nitrous oxide emissions, while the second plant has had an inconsistent history of abatement but announced in 2023 new abatement investment funded by a voluntary carbon market. Although several of the adipic acid plants in China are abating nitrous oxide and Clean Development Mechanism (CDM) payments have been available in the 2000s under the Kyoto Protocol, emissions have increased substantially since then (Liang *et al.* 2024), suggesting that some plants cannot be abating a large fraction of their emissions. Furthermore, a protocol was established in 2023 through which adipic acid plants in China could receive carbon credit payments from a voluntary offset programme based in North America, designed to avoid issues that interfered with the intended outcomes of the CDM, but no data are yet available on the success of this programme.

5.2.2. Supporting feasibility analyses and cost estimates of emission abatement

The United States Environmental Protection Agency (US EPA) (2019) projected that without further abatement efforts, global nitrous oxide emissions from adipic and nitric acid production in 2050 will be nearly triple 2015 levels due to growing demand for nylon and fertilisers, and continued expansion of these industries. The US EPA study estimates, however, that 86 per cent and 88 per cent of emissions could be abated with existing technology by 2030 and 2050, respectively. Emissions abatement potentials and costs vary widely among countries and regions (Figure 5.1). The US EPA report estimates that the largest emitters, China and the US, could reach 61 per cent and 49 per cent respectively of their national abatement potential at break-even prices below USD 3,000 per tonne of nitrous oxide (USD 10 per tonne of carbon dioxide equivalent) and that 80 per cent of the global abatement potential is achievable at break-even prices between USD 0 and USD 6,000 per tonne of nitrous oxide (USD 0–20 per tonne of carbon dioxide equivalent). Abatement potential and costs reported by Harmsen *et al.* (2019) fall within this range. Experience with abatement in the EU suggests that costs were under EUR 1,500 per tonne of nitrous oxide (EUR 5 per tonne of carbon dioxide equivalent) (Winiwarter *et al.* 2018).

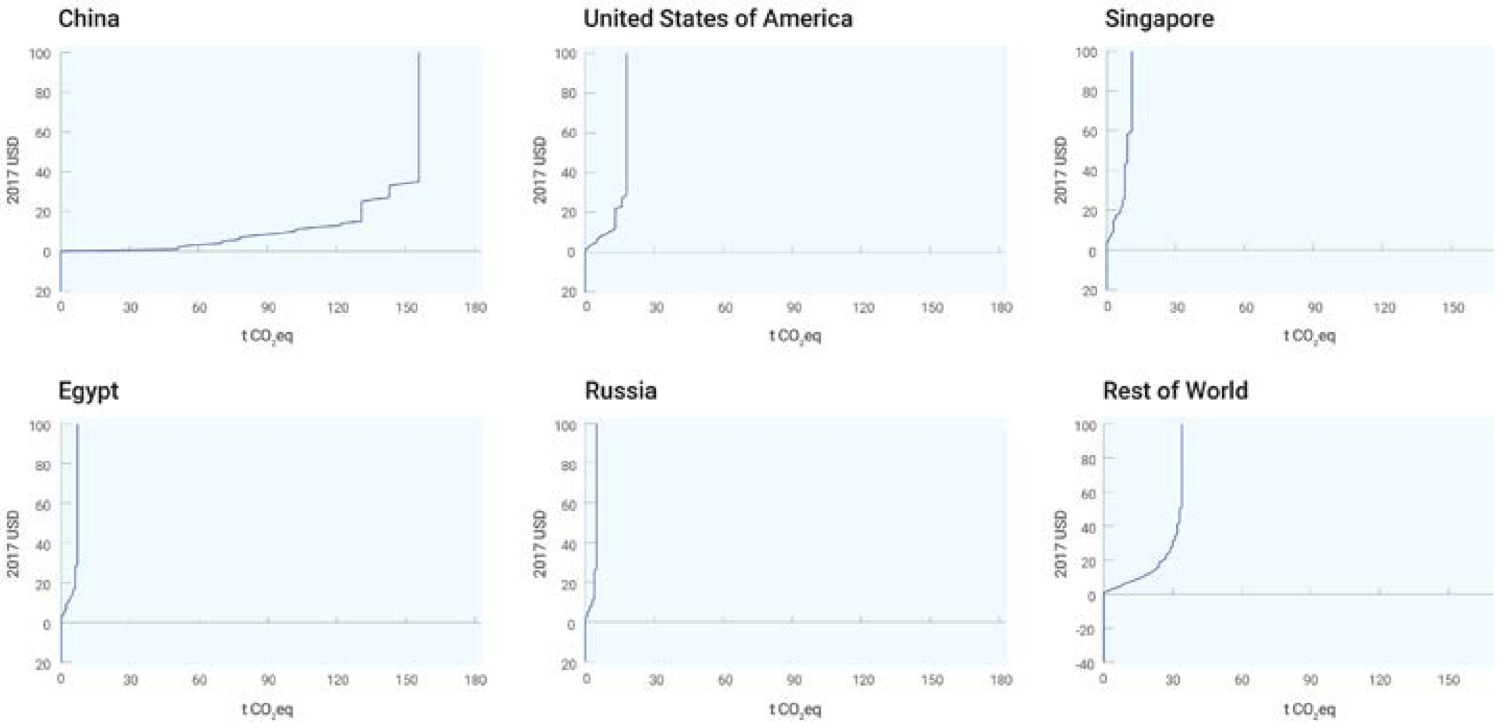

Figure 5.1 Marginal abatement cost curves for projected 2030 nitrous oxide emissions from adipic and nitric acid facilities for the top emitters and the rest of the world

Note: The horizontal axis shows the potential for emission abatement in metric tonnes of carbon dioxide equivalent, using 298 as the global warming potential for nitrous oxide relative to carbon dioxide instead of the 273 used in this Assessment. These potentials reflect each country's current emissions, for example, large in China and small in Russia. The vertical axis shows costs in 2017 dollars for each increment of additional abatement.

Source: US EPA 2019

Although abatement costs of nitrous oxide from adipic and nitric acid facilities are modest compared to those for many other greenhouse gas emissions, they are neither negative nor zero. Other measures have, therefore, been necessary to encourage most plant owners to install abatement equipment, including regulations and monetary incentives through voluntary carbon markets and mandated ETSs.

Photo: Saturnus99 / Pexels

5.2.3 Other industrial and energy-related emissions abatement

Additional nitrous oxide abatement is likely to occur in industry, energy production, transport, and heating sectors that currently rely on the combustion of fossil fuel, which produces a small amount of nitrous oxide as a by-product. As fossil fuels are replaced by renewable sources of energy and as the transport and heating sectors are electrified to reduce carbon dioxide emissions, nitrous oxide emissions will also decline as a co-benefit. Although not specifically motivated by abating nitrous oxide emissions, carbon dioxide emission abatement from these sectors should include the nitrous oxide emissions abatement in cost-benefit analyses.

5.3 AGRICULTURE – CROPLANDS AND GRASSLANDS

5.3.1 The potential for abatement

As described in Chapter 3, current efforts to abate nitrous oxide emissions from croplands and grasslands focus primarily on improving NUE of synthetic nitrogen fertilisers and manures applied to soils (Table 3.4), so that more of the applied nitrogen is taken up by crops and less is lost to the air and water. These measures may include enhanced-efficiency fertilisers (EEF) such as nitrification and urease inhibitors and slow-release fertilisers, amendments such as biochar and microbial inoculants, crop and cultivar choices, conservation tillage, and irrigation management. Ideally, these measures become part of a holistic nutrient management approach, such as the 4R concept of nutrient stewardship – the application of nutrients at the right rate, right type, right time, and right placement. The effectiveness of each measure is likely to be regionally or locally specific and may also have co-benefits for nutrient, water and energy management.

The technical scenario projections in this Assessment assume optimisation of fertiliser rates enabled by implementation of existing abatement measures, including lower losses of nitrogen from manure before being applied to soils. These measures will allow a significant reduction in fertiliser applications, while maintaining crop yields needed for projected food demands. Total cropland and grassland emissions of nitrous oxide in 2050 are projected to decline by about 26 per cent relative to 2020 emissions and about 44 per cent relative to the reference case 2050 emissions (Table 3.2). The technical reductions and societal change scenario projects further abatement due to changes in dietary choices that result in lower demand for fertilisers used to grow crops for animal feed (Table 3.2). Taken together, these measures are projected to decrease nitrous oxide emissions by more than 40 per cent relative to 2020 emissions and over 50 per cent relative to the reference case 2050 emissions (Table 3.2).

Photo: Tran Nam Trung/Pexels

5.3.2 Supporting feasibility analysis and cost estimates emission abatement

Most assessments assume that adoption of best management practices will enable reductions in the application of fertilisers. Gu *et al.* (2023), for example, used a meta-analysis of management effects and modelling of nitrogen budgets to estimate that optimising for cost-effective interventions (Figure 5.2) could reduce global use of synthetic nitrogen fertilisers by 21 per cent and decrease the global cropland nitrous oxide emissions by 50 per cent, while also meeting projected food demands.

Fertilisation rates would increase in some regions such as Sub-Saharan Africa, causing modest increases in nitrous oxide emissions, but this would be more than offset by reductions in regions where fertilisation rates are currently high, such as many parts of East Asia, South Asia, North America, and Europe.

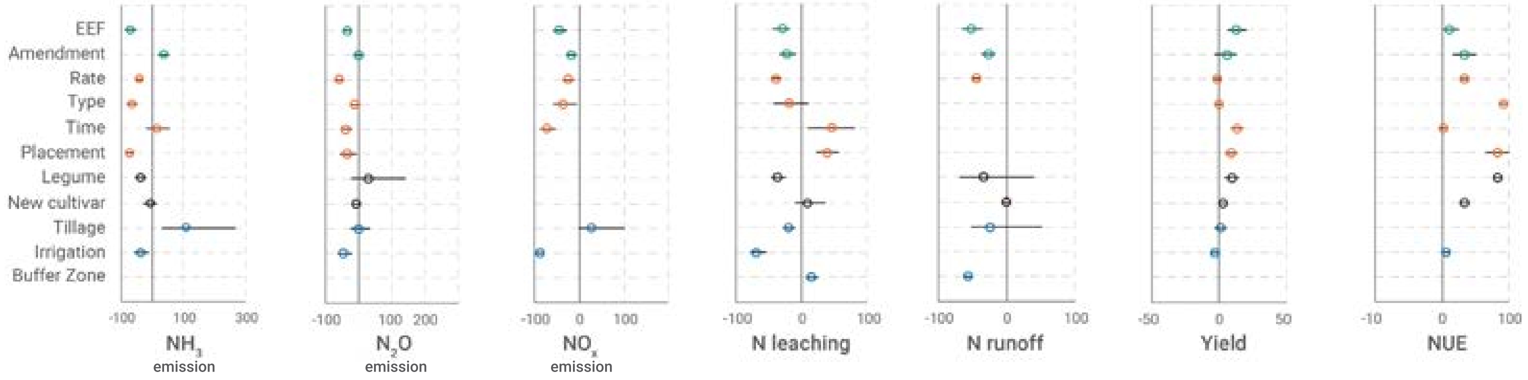

Figure 5.2 Meta-analysis results of effects of 4R nutrient management and related interventions to improve nitrogen use efficiency and reduce nitrous oxide emissions. All values given as per cent change.

Note: The 4R stewardship refers to the right fertiliser type, right amount, right placement and right time of fertilisation; EEF refers to enhanced-efficiency fertilisers; amend refers to amendments applied to croplands such as biochar; tillage refers to change from tillage to no-till; legume refers to rotation of legumes with other crops; irrigation refers to drip irrigation or optimal irrigation; buffer zone refers to the use of wetlands or marginal lands between croplands and rivers. The colours in the meta-analysis refer to different types of measures: additive (green), 4R nutrient stewardship (red), crop species (black) and biophysical management (blue).

Source: Gu *et al.* (2023)

Abatement of nitrous oxide emissions would be accompanied by reductions in other gaseous and leaching losses of nitrogen (Figure 5.2), resulting in additional human health, ecosystem health, and climate co-benefits (Figure 5.3). Despite the lower fertiliser application rates, the optimisation analysis also indicated increased crop yield, providing an additional cost benefit (Figure 5.3). The sum of the monetised human health, ecosystem health, climate and benefits are more than 10 times the estimated gross or net agronomic implementation costs. The fertiliser cost savings would be greatest in countries where application rates are currently high and NUE is low, such as China (Figure 5.3). Yield benefits would be greatest in countries where optimisation would increase nutrient additions, such as sub-Saharan Africa. Ecosystem benefits would be greatest where leaching losses of nitrogen are causing significant coastal eutrophication, such as China, North America, and Europe.

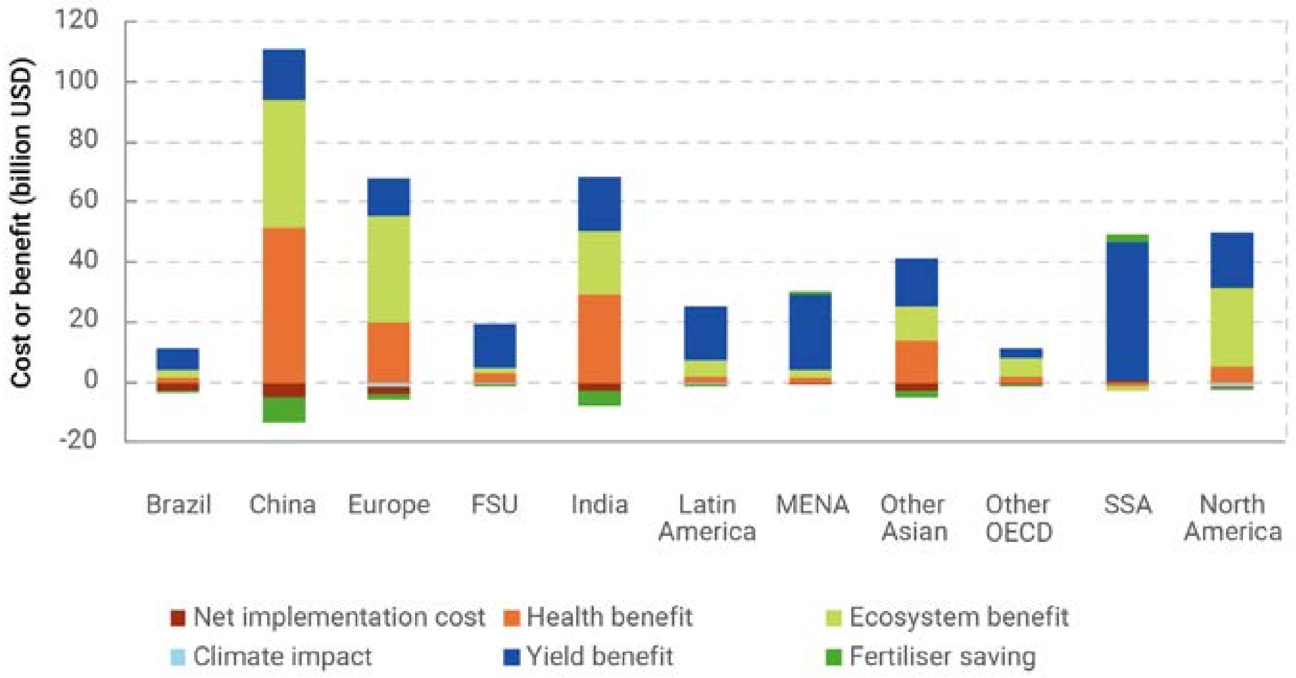

Figure 5.3 Costs and benefits of implementation, in 2015, of 11 selected measures shown in Figure 5.2, billion dollars

Note: Total costs and benefits are shown for the main global regions in 2015 under optimal mitigation options. Negative values refer to costs and positive values refer to benefits. Implementation costs refer to the net costs for farmers to implement measures accounting for fertiliser savings. FSU = Former Soviet Union; MENA = Middle East and North Africa; SSA = Sub-Saharan Africa. Source: Gu *et al.* (2023)

Cui *et al.* (2024) estimated that potential global abatement of fertiliser-induced nitrous oxide from croplands was 53 per cent, 5 per cent and 3 per cent of current emissions for improved fertiliser management, irrigation, and shifting diets, respectively. Abatement resulting from assumed adoption of the planetary health diet of the EAT-Lancet Commission was due to the reduction in the area planted in corn for animal feed, which would reduce fertiliser demand. These emission reductions, however, were partially offset by emissions from the increased areas planted with fruit, vegetables and oil crops, which tend to have lower NUE than grains (Zhang *et al.* 2015).

Gao and Cabrera Serrenho (2023) projected emissions and abatement potentials to 2050. Assuming that globally averaged NUE could be increased from 42 per cent to 67 per cent through improved nutrient management, they calculated that fertiliser demand and total greenhouse gas emissions, which are predominantly nitrous oxide emissions in this case, could be reduced by 48 per cent relative to their BAU projection for 2050. The authors considered the use of nitrification inhibitors to be an additional intervention, which they calculated could reduce emissions by 29 per cent relative to the 2050 BAU projection.

Few estimates of abatement costs for global cropland nitrous oxide emissions are available. In the study by Gu *et al.* (2023), the gross and net implementation costs of fertiliser optimisation were estimated at USD 34 (± USD 9) billion and USD 19 (± USD 5) billion, with the savings in fertiliser costs estimated at USD 15 (± USD 4) billion. Assuming a reduction of about 3 Mt nitrous oxide and ignoring other ecosystem and human health benefits, the USD 19 billion net cost is equivalent to about USD 6,300/t N_2O (USD 23/t CO_2e) and the USD 34 billion gross implementation cost is equivalent to about USD 11,000/t N_2O (USD 42/t CO_2e). Although expressed as a cost per unit of nitrous oxide abatement, these costs are actually for overall fertiliser optimisation, which would yield other agronomic, environmental, and human health co-benefits.

Harmsen *et al.* (2019) estimated a maximum of 47 per cent nitrous oxide emissions reduction from fertiliser optimisation practices by 2050 at USD 15,000/t N_2O (USD 51/t CO_2e), in 2010 US dollars. Winiwarter *et al.* (2018)

estimated costs of three abatement measures: EUR 1,500-28000/t N_2O (EUR 5–94/t CO_2e) for a 19–24 per cent reduction by variable rate technology – varying fertiliser application rates according to the needs of each area within a field; EUR 15,000–30,000/t N_2O (EUR 51–101/t CO_2e) for a 34-38 per cent reduction by microbial inhibitors – urease and nitrification inhibitors; and EUR 230,000–477,000/t N_2O (EUR775–1600/t CO_2e) for a 36-40 per cent reduction by precision agriculture technology – assisting management decisions using high-technology sensors and analysis tools.


Photo: Orhanveliakbaba/Pexels

Adoption of technologies to improve NUE and reduce nitrous oxide emissions involves more than developing and introducing technological options. It should be noted that the cost estimates cited above refer to implementation costs and may not include the regionally-specific financial incentives needed to encourage farmer adoption. The human health, ecosystem health and climate co-benefits (Figure 5.3) could justify cost sharing of implementation costs through innovative public policies and financial incentives. Economic considerations, including those under farmers' control and those that are imposed by policies and markets, are crucial for farmer decision making. In addition, social factors, such as farmer demographics and their perceptions of trusted sources of information are also important influences (Davidson *et al.* 2015). The importance of farmer adoption of best management practices and technologies for nitrous oxide abatement and other nitrogen pollution mitigation should not be underestimated, and should be a key focus of future research efforts.

BOX 5.1

COMPARISON OF COUNTRY-SPECIFIC MARGINAL ABATEMENT COST CURVES FOR THE UNITED STATES AND CHINA

As shown in Figure 5.3, the costs of nitrous oxide abatement in croplands and savings from reduced fertiliser use vary across regions because of differences in current fertiliser application rates and the potential to reduce them without decreasing yields. In the US, average NUE is already relatively high at about 68 per cent (Zhang et al. 2015), and so the opportunity to reduce average fertiliser application rates is present but may be more limited than in countries with lower NUE. There are, nonetheless, hot spots of opportunity for improving cropland nitrogen management in the US as well (Roy et al. 2021).

The United States Department of Agriculture (USDA) constructed marginal abatement cost curves, MACCs, for greenhouse gas emission reduction, primarily nitrous oxide in this case, from variable rate technology (VRT) and EEFs for US croplands (Jaglo et al. 2023). They assumed that these technologies could allow an average 10 per cent reduction in fertiliser-nitrogen application rates, and they modelled the net costs with and without a 1 per cent average increase in crop yield (Figure 5.4).

The maximum potential nitrous oxide abatement estimate for US croplands was 43,000 and 9,000 t N_2O/yr for EEF and VRT, respectively. Without an assumed yield enhancement, all marginal abatement costs exceeded USD 30,000/t N_2O (about USD 100/t CO_2e) for EEF and 90 per cent exceeded these costs for VRT. When a modest yield boost was assumed, about 75 per cent of the marginal abatement costs were less than USD 0/t N_2O for both technologies and nearly all were less than USD 30,000/t N_2O (about USD 100/t CO_2e) for EEF (Figure 5.4).

A literature review of all improved nitrogen management measures for nitrous oxide abatement by the Environmental Defense Fund (Eagle et al. 2022) found similar maximum abatement potential for US croplands, with 19,000, 32,000 and 48,000 t N_2O/yr abatement at USD 3,000, USD 15,000, and USD 30,000/t N_2O (about USD 10, USD 50 and USD 100/t CO_2e), respectively.

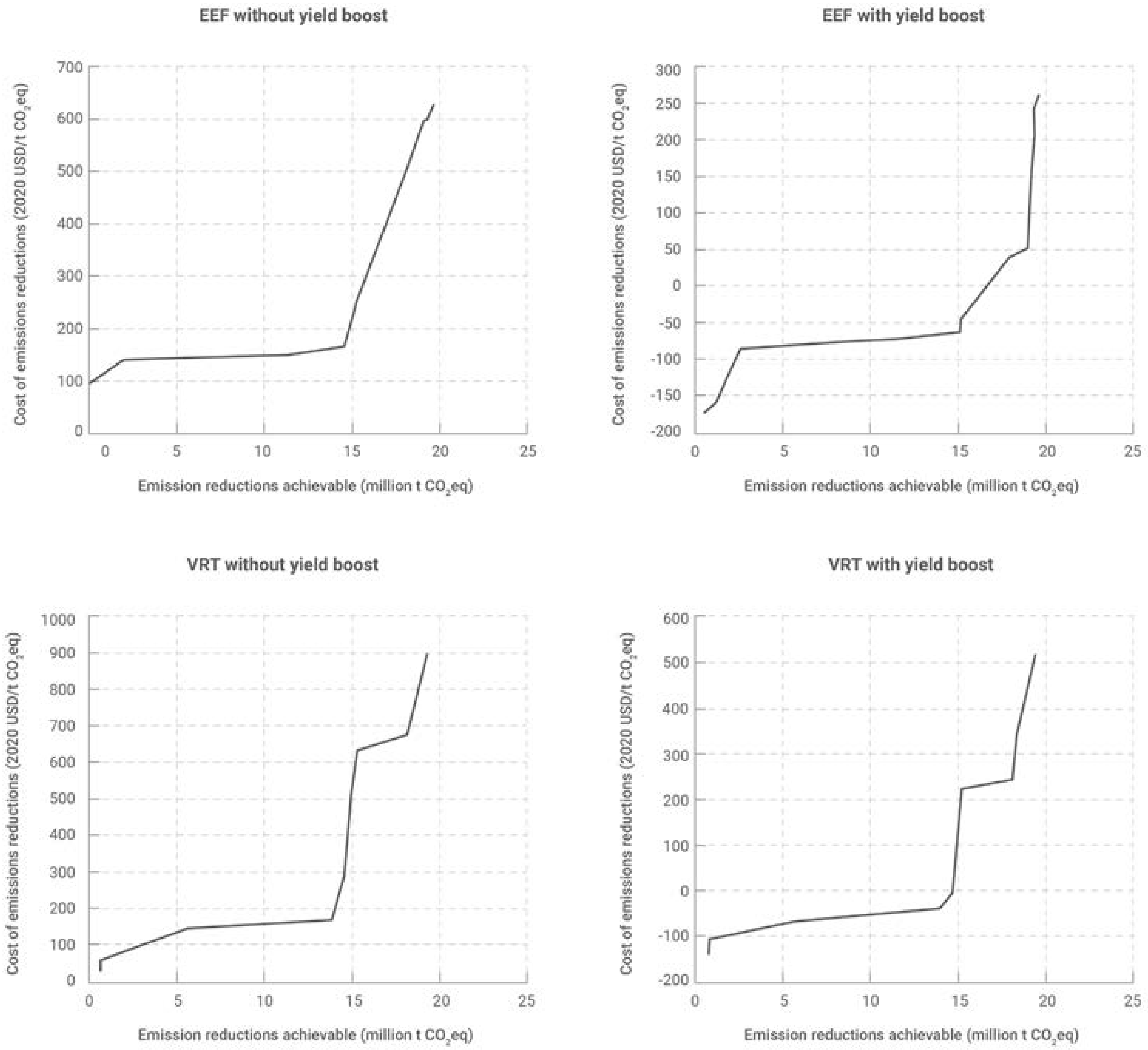

Figure 5.4 Marginal abatement cost curves for nitrous oxide emission reduction due to adoption of enhanced efficiency fertilisers (EEF) and variable rate technology (VRT) on US croplands, resulting in an assumed 10 per cent reduction in fertiliser rate application, with and without a modelled 1 per cent boost in crop yield.
Note: Values in parenthesis indicate negative costs.
Source: Jaglo *et al.* 2023.

Recent marginal cost abatement curves in China span several sectors in addition to agriculture, including 19 nitrous oxide mitigation measures, with their technical potential and marginal abatement costs for 2020 (Figure 5.5) (Xu *et al.* 2024). The MACCs indicate that China's nitrous oxide reduction potential is 1.2 Mt N_2O/yr, with total implementation costs summing to $26 billion, and an average abatement cost of $22,000/t nitrous oxide (about USD 81/t CO_2e). Agriculture contributes over half of nitrous oxide reduction potential, with key abatement measures including 4R fertiliser stewardship implementation 18 per cent; improved manure management 14 per cent; and innovative soil/crop management 5 per cent. The cost of agricultural measures accounts for 85 per cent of the total cost, approximately USD 22 billion. Among these, crop system measures cost USD 12 billion, with the marginal cost of 4R fertilisation being the highest at USD 49,000/t N_2O ($180/t CO_2e), while optimised irrigation and soil/crop management (tillage, cover crops, organic amendments) are relatively cost effective, with marginal abatement costs of USD 20,500/t N_2O (USD 75/t CO_2e) and USD 16,400/t N_2O (USD 60/t CO_2e), respectively.

The abatement cost in livestock farming is estimated at USD 9 billion, with grazing management being the most expensive at USD 78,600/t N_2O (USD 288/t CO_2e), manure management at USD 30,000/t N_2O (USD 110 /t CO_2e), and animal management at USD 16,400/t N_2O (USD 60/t CO_2e).

The industrial sector contributes 28 per cent of nitrous oxide reductions, primarily benefiting from process optimisation and waste reduction, 21 per cent, and advanced emission control technologies 7 per cent. The marginal abatement costs for these two technologies are low, at only USD 3,800/t N_2O (USD 14/t CO_2e) and USD 1,600/t N_2O (USD 6/t CO_2e). The residential, transport and energy sectors contribute 11 per cent, 5 per cent, and 4 per cent of the reductions, respectively. Effective reduction measures of these sectors include wastewater management at USD 5,500/t N_2O (USD 20/t CO_2e), promoting electric vehicles at USD 13,700/t N_2O (USD 50/t CO_2e) and improving fuel quality and productivity USD 27,300/t N_2O (USD 100/t CO_2e).

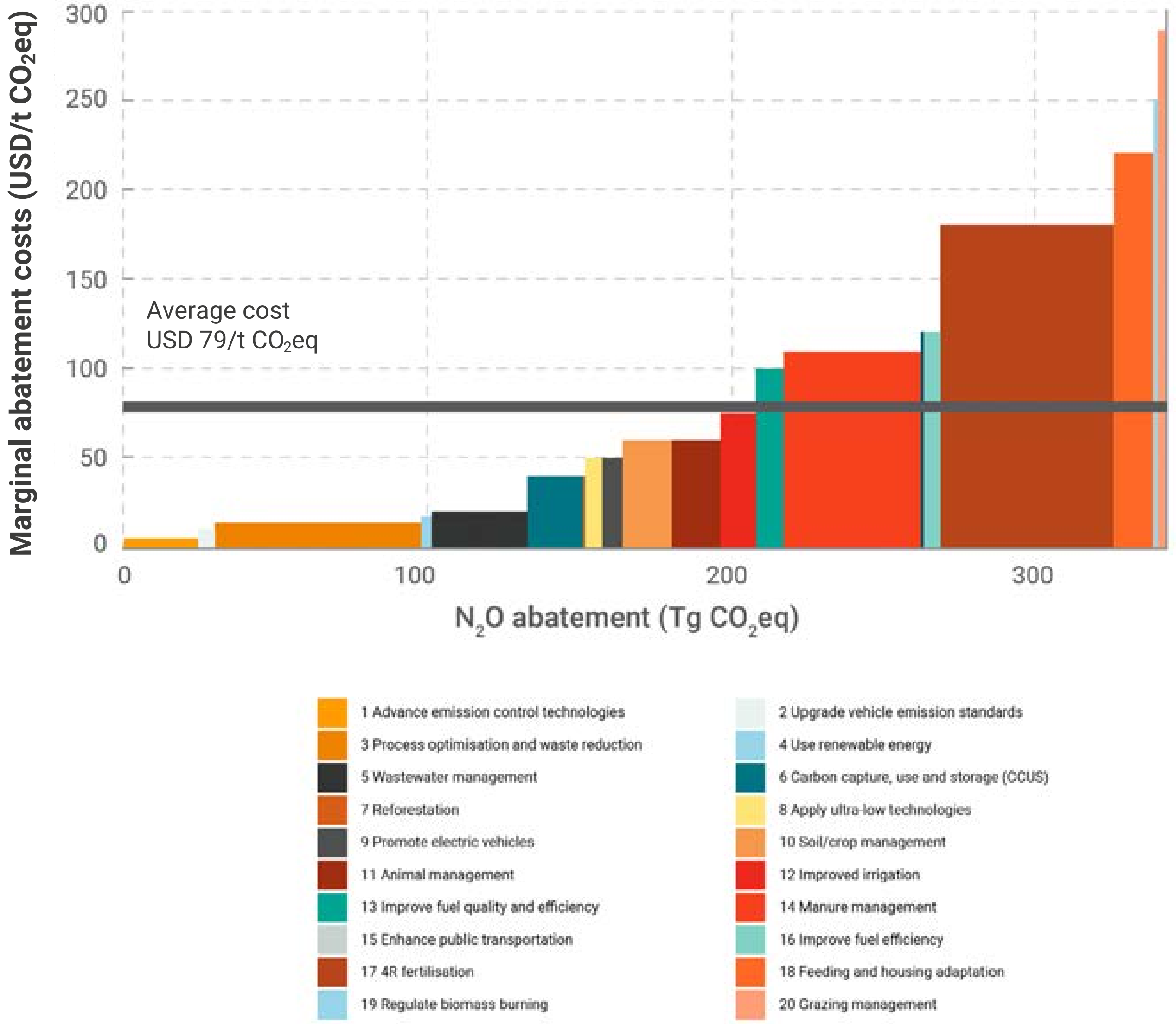

Figure 5.5 Marginal abatement costs curve of nitrous oxide emission in China across different sectors, 2020, US dollars per tonne of carbon dioxide equivalent
Source: From Gu *et al.* (2024) using cost calculation methods of Winiwarter *et al.* (2018) and Feng *et al.* (2024) and data from references in Supplemental Information Table 5.1.

AGRICULTURE – LIVESTOCK AND MANURE MANAGEMENT

Emissions of nitrous oxide occur when manure is applied to cropland soils and when manure is applied or directly deposited by animals on pasture soils (Fig 5.6a), and those emissions are included in Section 5.2 on croplands and grasslands. This Assessment projects reduced emissions of nitrous oxide from croplands due to more efficient use of manure, thus displacing fertiliser uses in the technical reductions scenario (Table 3.4). Further nitrous oxide abatement from manure management is considered in the technical reductions and societal change scenario (Tables 3.2 and 3.3), in which animal numbers and therefore manure production decline due to changes in human dietary preferences.


Photo: Matt Barnard/Pexels

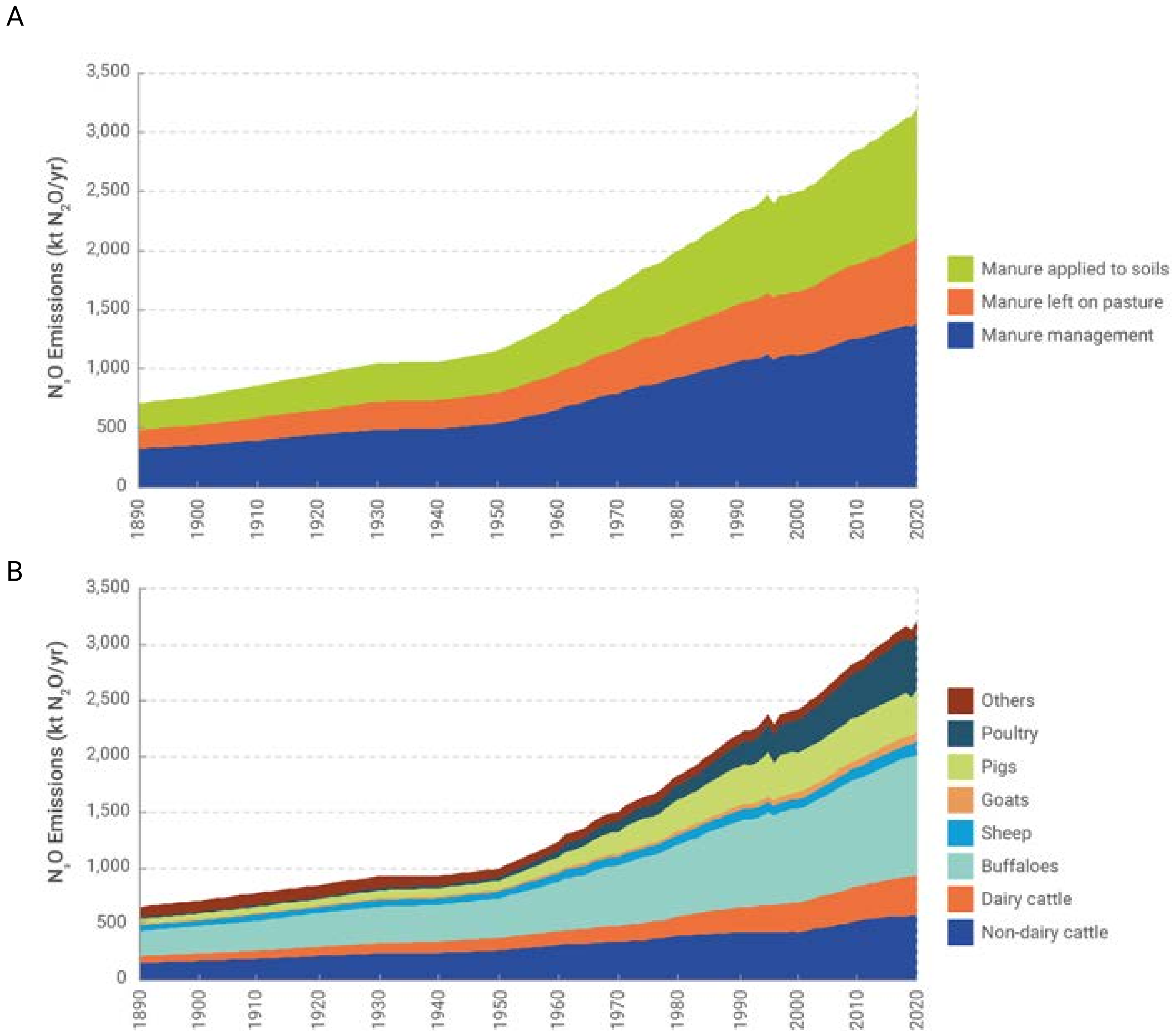

Figure 5.6 Global emissions of nitrous oxide from manure by management type (A) and by animal group (B), 1890–2020, megatonnes of nitrogen per year
From Zhang *et al.* 2024

Additional abatement is possible through handling, storage and improved management of manure. Manure from dairy and non-dairy cattle contribute more than 50 per cent of the total, and are therefore the largest target for abatement, although emissions from poultry manure have increased significantly in the last 30 years (Uwizeye *et al.* 2020; Zhang *et al.* 2024) (Figure 5.6). Strategies to reduce emissions from manure management include improving the balance of nutrient inputs in animal feed, reducing grazing intensity, anaerobic digestion of manure, decreased manure storage time, sealed manure storage with flaring, timing of manure application to soils, application of nitrification inhibitors to manure or following urine deposition on to soils, application of urease inhibitors with or before urine deposition onto soils, and management of soil water content and drainage (Montes *et al.* 2013). Abatement of nitrous oxide emissions from grazing systems is more challenging, but the implementation of silvopastoral systems has been shown to reduce nitrous oxide emissions by improving soil cover and increasing sinks for added nitrogen, and by improving diet quality and increasing condensed tannin content in the diet (Rivera and Chará 2021).

Tradeoffs and synergies with other pollutant mitigation efforts must be considered (Montes *et al.* 2013; Sajeev *et al.* 2018; Rivera and Chará 2021). Nitrous oxide and ammonia emissions can be reduced by, for example, lowering the crude protein content in animal feed, but that may also increase methane emissions from ruminants. Manure aeration, covering manure during storage and air scrubbers in animal housing facilities can reduce methane and ammonia emissions but increase those from nitrous oxide. Urease inhibitors can reduce both nitrous oxide and ammonia emissions. Properly functioning anaerobic digesters can reduce both nitrous oxide and methane emissions. Manure acidification can reduce emissions of all three gases.

Because emissions of methane and nitrous oxide from manure and its management are so intertwined, cost abatement estimates often include both gases combined into a single global warming potential metric (US EPA 2019). Harmsen *et al.* (2019), however, estimated a specific global potential of 1.6 Mt nitrous oxide through improved animal diet and housing and manure storage, with an average cost of USD 17,600/t N_2O (USD 59/t CO_2e). In China, a more aggressive manure management abatement potential was estimated at 180,000 tN_2O with an average cost of USD 30,000/t N_2O (USD 110/t CO_2e) (Box 5.1).

Abatement measures designed to reduce nitrous oxide emissions from the livestock sector would likely have additional co-benefits, including healthier human diets that are more plant-based and improved air quality for residences located near livestock facilities, which are often low-income communities.

Photo: William Richardson/Adobe Stock

5.5 AQUACULTURE

Aquaculture is a relatively minor contributor and not included in this Assessment as a sector for significant reduction of current emissions. The growth of this sector for food production is, however, about 7 per cent per year and is projected to increase its contribution to total anthropogenic nitrous oxide emissions to more than 6 per cent by 2030 (Hu *et al.* 2012). Only about 25 per cent of the nitrogen in feed is typically recovered in the fish biomass, with the remainder causing significant accumulation of waste products and gaseous emissions (Figure 5.7). Efforts to mitigate nitrous oxide emissions from aquaculture systems are usually consistent with optimisation for productivity, because excess nutrients are usually detrimental to the production systems (Hu *et al.* 2012). Hence, the most common approach to abating nitrous oxide emissions is through system optimisation, such as integrating recirculating aquaponic systems with polycultures of plant sinks for nitrogen. Beneficial heterotrophic bacteria can also be promoted to assimilate inorganic nitrogen and improve its recycling. Optimisation also includes managing dissolved oxygen, temperature, acidity, salinity and substrate levels through the use of aerators, periodic changes in water, and managing the content, nitrogen and other nutrients in feed (Zhou *et al.* 2021). Emission factors range widely among fish and other aquatic species, indicating that the choice of species is another potentially effective abatement strategy (Zhou *et al.* 2021). Additives such as polylactic acid have been shown to stimulate denitrification to molecular nitrogen, thus removing excess nitrogen from fish excreta and lowering nitrous oxide emissions (Zou *et al.* 2017). As far as can be ascertained, cost abatement estimates have not been published but the commonality of reducing excess nitrogen wastes for both nitrous oxide abatement and improved system productivity suggest that the net costs are likely to be low or even negative.

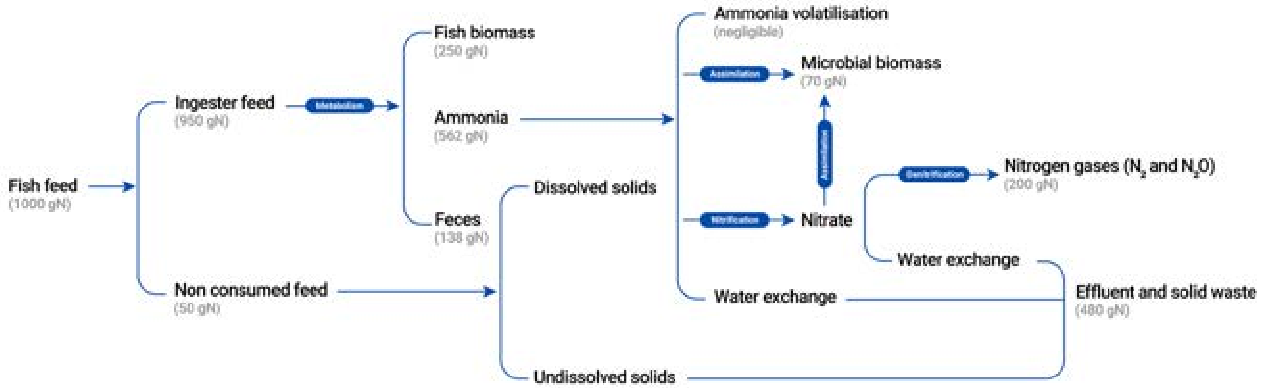

Figure 5.7 An example of a nitrogen budget in an aquaculture system
Source: Hu *et al.* 2012

5.6 WASTEWATER

Nitrous oxide emissions from the biological processes of nitrification and denitrification account for 50–80 per cent of the greenhouse gas emissions of wastewater treatment plants (WWTP) (Vasilaki *et al.* 2019). The technical reductions scenario of this Assessment projects an abatement of 2050 nitrous oxide emissions by about 30 per cent relative to the reference scenario (Table 3.3). Between 1990 and 2019, nitrous oxide emissions from domestic wastewater treatment in the EU decreased by 17 per cent due to the application of new wastewater treatment processes (Maktabifard *et al.* 2023). In contrast, a 42 per cent increase was reported for the US due to population growth and increased protein consumption.


Photo: Orhanveliakbaba/Pexels

Current abatement strategies include aeration control, feed-scheme optimisation and process optimisation (Duan *et al.* 2021). A mitigation strategy shown to be effective in one WWTP may not, however, be applicable to another, suggesting that mitigation strategies are best developed on a case-by-case basis (Maktabifard *et al.* 2023). Critical technical challenges include improvements for nitrous oxide quantification methods, systems modelling to enable comparisons of mitigation strategies, risk assessments regarding operational costs and nutrient removal performance, studies of decentralised wastewater management systems, and investigation of novel strategies (Duan *et al.* 2021). Novel strategies include source separation, such as urine separation, which could potentially abate 60 per cent of nitrous oxide emissions while also recovering nutrients that could offset nitrogen fertiliser applications to croplands (Maktabifard *et al.* 2023). Recovering and utilising nitrous oxide for energy production has shown promise in the laboratory, but is technically and economically challenging (He *et al.* 2023).

Because of the variety of mitigation strategies and lack of sufficient field scale tests, there are few estimates of abatement costs. Winiwarter *et al.* (2018) report that nitrous oxide emissions could be reduced by 40 per cent through optimisation of WWTPs at no net additional cost where secondary or tertiary treatment is already available. Some abatement strategies require added energy consumption or the addition of a carbon source, but nitrous oxide mitigation does not necessarily result in additional operational cost or lower removal efficiency and may produce energy savings and reduced costs. Indeed, reducing costs through energy saving are incentivising upgrades to WWTPs, and nitrous oxide and methane abatement strategies could be integrated into the optimisation of upgraded processes (Duan *et al.* 2021). Emissions trading schemes could also help finance WWTP optimisation but have been underutilised to date (Duan *et al.* 2021). The current research emphasis on centralised WWTPs has resulted in less knowledge about emissions and their abatement in smaller, decentralised systems. Where secondary and tertiary wastewater treatment facilities are inadequate or nonexistent, investment in sewage treatment is likely to be to driven primarily by concerns about human health and downstream water quality, but nitrous oxide abatement would accompany improved sewage treatment as an important co-benefit.

Photo: Pok Rie/Pexels

5.7 SUMMARY OF ABATEMENT POTENTIALS ACROSS SECTORS

The abatement potential is greatest for the current large emissions from croplands and grasslands, but the estimated costs are highest (Table 5.1). In contrast, the smaller emissions from adipic and nitric acid production could be almost completely eliminated and are the least expensive, suggesting a modest but important low-hanging fruit opportunity. Abatement opportunities from other sectors are also modest but may come as co-benefits of decarbonisation and other optimisation efforts related to those sectors. The total 2050 abatement potential of the technical reductions and societal change scenario is 44 per cent of 2020 emissions and 56 per cent of the projected reference case 2050 emissions.

Abatement potentials are often not realised due to sufficient lack of information and socio-economic factors that affect adoption of best practices and new technologies. Optimisation of fertiliser application rates is inherently challenging in light of spatial and temporal variation in soils, cropping systems, climate and socio-economic drivers of farmer decision making. Whether human diets will be modified sufficiently to reduce animal numbers is highly uncertain. Assuming that the abatement potentials presented here will likely be achieved may present a moral hazard, which is not the intention of this Assessment. Rather, abatement potentials are presented to demonstrate what effective policies could achieve if rigorously pursued.

Table 5.1 Summary of abatement potentials projected in this Assessment and ranges of reported abatement costs

Sector	Abatement potential: 2050 technical reductions and societal change scenario relative to the reference scenario. (2020 emissions)	Abatement potential: 2050 technical reductions and societal change scenario relative to the reference scenario. (2050 emissions)	Range of abatement costs		Comments
	t nitrous oxide		USD/t nitrous oxide	USD/t CO_2e	
Industry (adipic & nitric acid)	420,000	600,000	1,600– 6,000	6–22	
Industry – fossil fuel combustion	380,000	460,000	Not applicable		Co-benefit of decarbonisation
Agriculture – croplands & grasslands	3,050,000	5,110,000	6,300– 49,000	23–180	Varies with type of intervention
Agriculture – livestock & manure management	100,000	320,000	18,000– 30,000	60–110	Co-benefit with dietary changes in this Assessment
Wastewater	230,000	430,000	$5,500	20	Likely accompanies optimisation for energy and treatment performance
Total	4,180,000	6,920,000			

Note: t = tonnes

5.8 TRANSFORMATIVE CHANGES THAT COULD ENABLE DEEPER EMISSION ABATEMENT

Most approaches to nitrous oxide abatement, including those considered in the scenarios of this assessment, rely on improved efficiencies of current processes. This is probably sufficient for abating nearly all emissions from industrial sources. The most likely abatement of nitrous oxide emissions from fossil fuel combustion in energy, transport, and heating sectors is likely to be dependent upon transforming and redesigning those sectors to utilise renewable sources of energy (Davidson and Winiwarter 2023). In agriculture, incremental steps with existing or emerging technologies can also yield significant emissions abatement, but deeper mitigation by 2050 may require significant innovation and the redesign of food production systems (Houlton *et al.* 2019; Northrup *et al.* 2021).

For most of human history, farmers relied on natural sources of nitrogen, such as natural soil fertility and manure additions, to grow crops; that pre-fertiliser system could be called Nitrogen 0.0. As populations rose rapidly in the 19th century, this system was inadequate to meet the growing demand for food. Discovery in the early 20th century of the Haber-Bosch process to synthesise ammonia from molecular nitrogen and hydrogen at high temperature and pressure led to large-scale production of synthetic nitrogen fertilisers by the mid-century, revolutionising agriculture and greatly improving average human nutrition and food security but also leading to unsustainable losses of nitrogen to air as ammonia, nitrogen oxides and nitrous oxide, and to water as nitrate and dissolved organic nitrogen. The current food production system, which could be called Nitrogen 1.0, is a mostly linear and leaky system of nitrogen use in agriculture (Figure 5.8a). The incremental abatement measures described above can reduce such leaks of nitrous oxide from the food production system, perhaps by as much as 50 per cent under high ambition for the adoption of existing and emerging technologies by farmers. To achieve the most ambitioius abatement scenarios, however, it may also be necessary to envision a more transformational food production system that is more circular, targeted and efficient. The needed transformation would yield major reductions in nitrous oxide emissions and other forms of nitrogen losses to the environment, while also ensuring the high agricultural productivity needed to meet growing human needs for healthy, affordable diets and food security. This new vision could be called Nitrogen 2.0 (Figure 5.8b), which includes transformational innovation that will require new investments in research and development in both private and public sectors.

First, increased use of traditional and novel forms of non-crop nitrogen fed directly to animals would reduce the dependence on the nitrogen-leaky crop production system, essentially skipping a trophic level and its inefficiencies for a significant fraction of animal feed. Feed additions may include supplemental amino acids, other non-protein sources of nitrogen, microbial biomass specially designed for animal feed, nitrogen-enriched silage and other products (Kim *et al.* 2019). Improved management of feed composition could also improve digestibility and reduce nitrogen concentrations in animal wastes. By targeting more nitrogen additions directly to livestock feed, the demand for crude protein from crops for animal feed would decline, thus avoiding much of the nitrogen leakage to air and water that accompanies fertilised crop production for animal feed. Animal breeding may also allow a broader range of nitrogen sources in feed as well as manure characteristics that enable improved manure management and recycling. Complementary proteins may also be developed for direct human consumption, although a longer time horizon may be needed to modify human dietary options.

Second, possibilities will emerge for new cropping systems, land uses and attendant changes in fertiliser use as a result of changes in livestock feed options (Northrup *et al.* 2021). With enrichment of animal feed with synthetic nitrogen and less demand for nitrogen in crop-based crude protein for livestock feed, corn, for example, can be bred for lower nitrogen content in the grain, as low as 4 per cent protein, for use as feed and biofuel. Crop breeding can also improve within-cropland recycling of nitrogen through a number of strategies that mimic perennial systems, such as cold tolerance for longer growing seasons and recycling of nitrogen to roots in the autumn. Soil communities of nitrous oxide-respiring bacteria may also be selected for their capacity to thrive in soil (Awala *et al.* 2024; Hiis *et al.* 2024). A greater diversity of crops could be grown for direct human consumption, while conservation land could increase as less cropland is needed to produce crude plant protein for livestock.


Photo: Zorgens/Adobe Stock

Third, Nitrogen 2.0 also envisions large improvements in capture of manure nitrogen within manuresheds and subsequent increased recycling on to croplands, thus re-integrating crop and animal production systems and improving the circularity of the overall food production system (Spiegal *et al.* 2022). Anaerobic digestion could produce energy for on- or off-farm use as well as produce a nutrient- rich, odourless digestate well suited for soil enhancement, and composting could also improve the recyclability of manure (Lim *et al.* 2023). Greater circularity of nutrient dynamics would decrease demand for inputs of synthetic nitrogen fertilisers. Recovery of human wastes for recycling or for other uses such as energy production, fertiliser or feed production may also be improved, although this may require longer-term research and development (Marchuk *et al.* 2023).

Fourth, the use of human food waste as livestock feed (Dou *et al.* 2018) or for composting for crop and horticultural use (Pérez *et al.* 2023), while facing significant health and safety issues and regulatory constraints, has been undervalued and underutilised. Overcoming technical and socio-economic hurdles for its use as a nitrogen and energy resource could reduce the demand for fertilisers and livestock feed, and the attendant nitrous oxide emissions.

The Nitrogen 2.0 transformative vision is consistent with, but goes well beyond, the incremental implementation of abatement measures projected in this Assessment, such as implementation of 4Rs nutrient stewardship, enhanced efficiency fertilisers, other soil amendments, conservation tillage and dietary changes. It is not mutually exclusive with other possible technological breakthroughs, such as genetic modification for biological nitrogen fixation in grains or development of high yielding perennial crops. Nor does it preclude or depend upon an uncertain social acceptance of large-scale dietary changes. Rather, Nitrogen 2.0 focuses on transformational changes that could be achieved within the next few decades with appropriate investment in research and development to substantially improve targeted efficiencies and circularities.

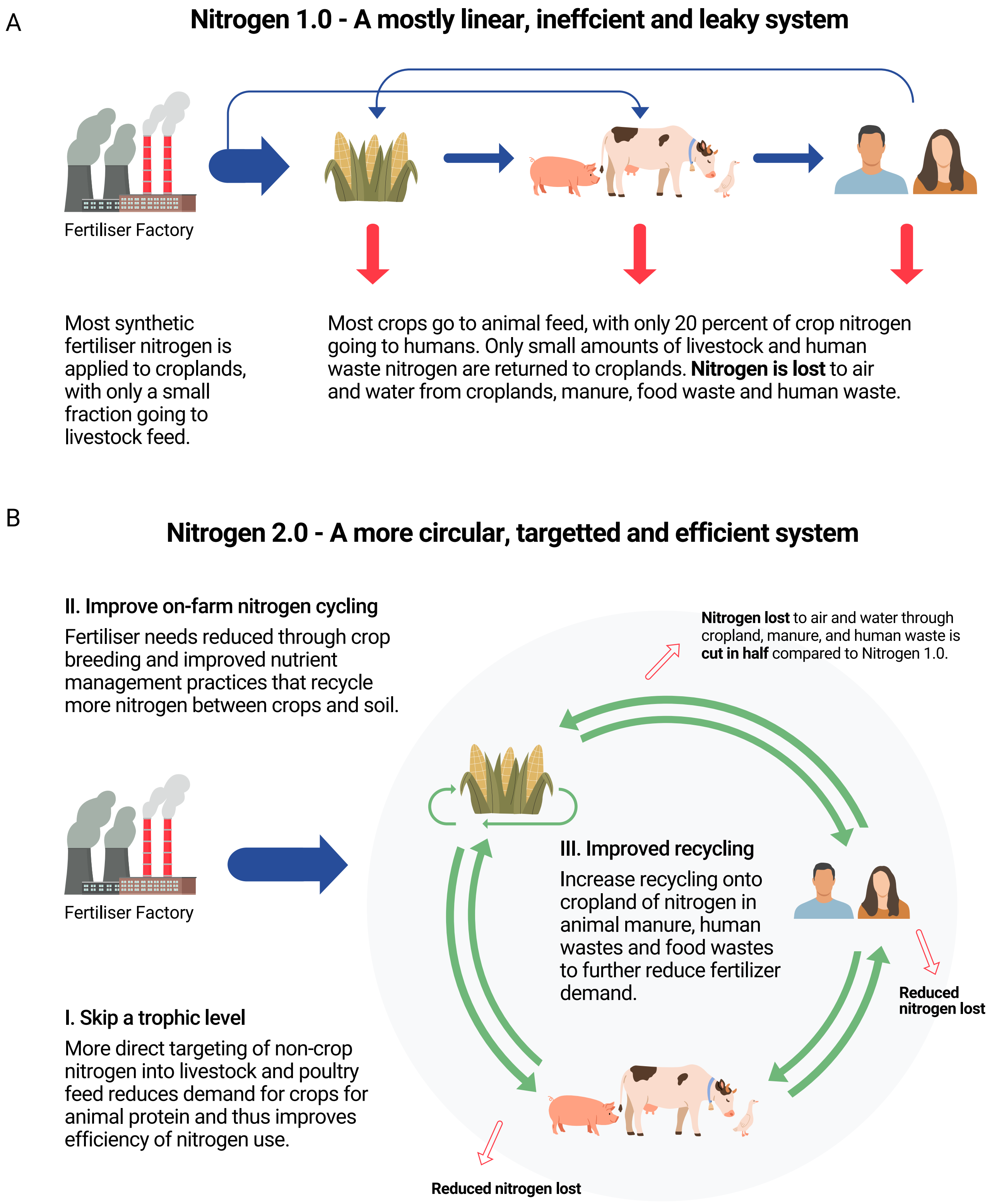

Figure 5.8 Schematic diagrams of the current, mostly linear and leaky food production system, Nitrogen 1.0, and a transformational vision for a more targeted, circular and efficient system, Nitrogen 2.0.

5.9 SOCIAL COSTS OF NITROUS OXIDE

Estimating a pollutant's social cost is one of the most widely used approaches to quantify the economic damage to society caused when it is lost to the environment. The dollar value of a social cost represents the marginal economic damage generated by the emission of an additional unit of a pollutant (Kanter *et al.* 2021). As such it is an important complement to the estimate of abatement costs discussed above by enabling a preliminary comparison of the costs and benefits of different policy options. As noted throughout this Assessment, a sustainable nitrogen management approach to nitrous oxide abatement could deliver multiple co-benefits by reducing the losses of several nitrogen compounds, each with their own social cost. These costs are evaluated in detail in the forthcoming International Nitrogen Assessment. The analysis in this section, consistent with this assessment, is limited to nitrous oxide.


Photo: Ouajbir/Pexels

For stratospheric ozone depletion, Compton *et al.* (2011) estimate the human health costs of nitrous oxide's contribution to increased ultraviolet exposure by scaling trichlorofluoromethane damage costs to nitrous oxide's ozone depleting potential of 0.017. Meanwhile, the *European Nitrogen Assessment* (2013) and the forthcoming INA estimate ozone damage costs using disability-adjusted life years (DALYs) – a way of measuring the overall burden of disease, in which one DALY represents the loss of the equivalent of one year of full health. Most recently, nitrous oxide's damage factor was estimated at 2.2 × 105 DALY per kilogram of nitrogen for 2015 (Hayashi and Itsubo 2023), leading to the forthcoming INA estimate of nitrous oxide's social cost in terms of ozone impacts of USD 1,670/t N_2O (in 2020 US dollars).

A range of choices can then be made with respect to the discount rate applied to a social cost: for example, the 2023 US EPA updates use a medium cost rate of 2 per cent, the forthcoming INA follows Kikstra *et al.* (2021) in using a 1 per cent interest rate, while others use a growth-linked discounting framework that varies over time (Wang and Feng 2023).

Recent estimates of nitrous oxide's social costs show quite strong agreement despite the different discounting frameworks used (Table 5.2). The social cost estimates for nitrous oxide's climate impact focus solely on it and do not account for the short-term aerosol-masking effects associated with a sustainable nitrogen management approach, as examined in Chapter 4.

Table 5.2 - The nitrous oxide social costs for both ozone and climate damage from a range of recent estimates, tonnes of nitrous oxide, carbon dioxide equivalent and ozone-depletion potential, 2020 US dollars
Note: There are uncertainty ranges associated with each estimate – the numbers listed here are the median or medium estimates.

CLIMATE DAMAGE	2020 USD/t N_2O	2020 USD/t CO_2eq
ENA (2011)	25,500	90
US EPA (2023)	54,000	200
Wang and Teng (2023)	49,600	180
INA (forthcoming)	60,100	220
OZONE DAMAGES	**2020 USD/t N_2O**	**2020 USD/t CO_2eq**
Birch *et al.* (2011)	1,030	20
ENA (2011)	4,600	80
INA (forthcoming)	1,670	30

5.10 CONCLUSION

The studies assessed here suggest that an approximate 50 per cent abatement of nitrous oxide emissions is feasible by 2050 through a variety of measures in multiple sectors. The most immediate and cost-effective measures are in the industrial sector, whereas larger but more challenging and costly abatement opportunities exist in the agricultural sector. These include ambitious implementation of existing agricultural technologies and best management practices. Transitioning human diets away from animal products and toward more plant-based diets could also contribute to significant emissions reductions. For both crop and animal production systems, additional innovation and redesign of a more targeted, efficient and circular food production system with respect to nitrogen management will be needed for deeper nitrous oxide emission reductions.

CHAPTER 6:
CONCLUSION AND WAYS FORWARD

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The preceding chapters have outlined the trends, sources and environmental consequences posed by anthropogenic nitrous oxide emissions, the range of mitigation strategies available, and the environmental and human health co-benefits associated with ambitious abatement. Here four overarching points that should be core considerations for future action on nitrous oxide are highlighted, priority ways forward for policymakers, scientists and stakeholders identified, and the need for several key knowledge gaps to be addressed underlined.

6.1 CORE CONSIDERATIONS FOR FUTURE ACTION ON NITROUS OXIDE


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6.1.1. The importance of immediate action on nitrous oxide

Current climate policies prioritise action on the reduction of carbon dioxide and methane emissions and often neglect nitrous oxide. This could have serious consequences for the ozone layer, as well as more broadly for air and water quality and biodiversity loss, given the significant impacts of nitrogen loss on the environment and human health. Moreover, nitrous oxide's long atmospheric lifetime, coupled with its close interactions with other, more short-lived nitrogen compounds, notably ammonia and nitrogen oxides, means that the environmental and human health benefits of ambitious nitrous oxide abatement are likely to accrue over several decades. Ambitious nitrous oxide abatement under a sustainable nitrogen management approach will initially generate significant benefits for air quality, which in turn will avoid millions of premature deaths.

Meanwhile, the climate and ozone-layer benefits of ambitious abatement will be felt towards the second half of the 21st century, including, avoided skin cancers, cataracts and carbon dioxide equivalent emissions. These benefits will increase with time.

In all cases, delivering these benefits requires starting ambitious nitrous oxide abatement now.

6.1.2. The importance of an integrated approach to nitrogen

As noted throughout this Assessment, the unique chemistry of the nitrogen cycle demands an integrated approach to nitrous oxide abatement. This means accounting for all major nitrogen compounds in abatement action and avoiding or minimising measures that could risk pollution swapping, i.e., the abatement benefits from one compound is offset by an increase in another. Adopting such an integrated approach will likely generate very significant short-term co-benefits as noted in Chapter 4, such as large improvements in air and water quality, with concomitant improvements in human health, which will make it easier to achieve several other nitrogen-relevant commitments.

These include Target 7 of the post-2020 Global Biodiversity Framework, which calls for halving nutrient losses by 2030; the Gothenburg Protocol commitments under the Convention on Long-range Transboundary Air Pollution (CLRTAP); and several SDGs, such as Goal 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture; and Goal 6: Ensure availability and sustainable management of water and sanitation for all. It will also enhance societal resilience to some of the unavoidable impacts of climate change, and potentially avoid the need for drastic action to ward off the worst effects of climate change.

6.1.3. Balancing food security with environmental action

Agricultural nitrous oxide emissions are a by-product of agricultural nitrogen. Nitrogen – mostly from synthetic fertiliser and manure, but also from biological nitrogen fixation, atmospheric deposition and indigenous soil stores – fuels plant growth and is therefore foundational to the global food system. Ambitious nitrous oxide abatement is possible without threatening food security. Certain management practices and technologies can even make food production more resilient to current and future environmental challenges by, for example, prolonging the time that plant-available nitrogen is present in the soil (Chapter 5). Most current agricultural nitrogen policies, however, prioritise food security, for example, through fertiliser subsidies and trade rules, over environmental protection, which reduces the incentive to manage nitrogen more sustainably. Developing governance approaches that can balance the need for food security and environmental and health protection are crucial.

6.1.4. Incremental or transformative action

Many of the measures to abate nitrous oxide across all sectors can operate within current production systems, for example, using controlled-release fertilisers for crops or catalytic decomposition technologies in nitric and adipic acid production, do not require fundamentally new production processes but rather can be added to existing ones. Other action, however, requires more fundamental, systemic change, as outlined in Chapter 5. This is largely the case in agriculture and the broader agri-food system, ranging from the re-integration of crop and livestock production, the development and adoption of genetically-engineered plants and microbial solutions to transform non-leguminous crops into nitrogen fixers, and changes in consumer diets to significantly lower animal protein consumption. These kinds of systemic changes are likely to be necessary to go beyond 50 per cent abatement of nitrous oxide emissions from the agricultural sector and the global food system relative to 2020, as noted in Chapters 3 and 5.

Photo: Pixabay/Pexels

6.2 PRIORITIES FOR ABATEMENT

A multitude of policy options are currently feasible. Of the many abatement opportunities noted in Chapter 5, two are highlighted here – one is a low hanging fruit in terms of having market-ready and cost-effective abatement technologies readily available for nitric and adipic acid production, and the other, agriculture, is the most important in terms of scale.

Photo: NC Farm Bureau Mark/Pexels

6.2.1. Nitric and adipic acid production

Nitrous oxide from these sources is responsible for 5 per cent of current anthropogenic emissions, but these could increase by approximately 40 per cent by 2050 in this Assessment's reference scenario. As noted in Chapter 5, several abatement technologies, which have already been applied in several countries, have proven to be cost-effective and can abate emissions by more than 99 per cent without needing to transform the underlying production processes. As outlined in Chapter 3, action in these sectors could reduce emissions by approximately 2.5 billion tonnes of carbon dioxide equivalent and 160,000 tonnes of CFC-11 equivalent by 2050 compared to the reference scenario and would not require fundamental changes in production systems.

6.2.2. Agriculture

While nitrous oxide mitigation can be quickly achieved in non-agricultural sectors, ambitious abatement is only possible by meaningfully reducing emissions from agriculture and the broader food system.

A broad array of technological and behavioural measures already exist that have been shown to be effective in significantly reducing nitrous oxide emissions across a range of different regions, climates and production systems. In-depth analysis of these measures can be found in the Guidance Document on Integrated Sustainable Nitrogen Management (Sutton *et al.* 2022) and the forthcoming INA.

6.3 KNOWLEDGE GAPS

While there is sufficient scientific data and technology to support immediate action on nitrous oxide, the scientific community, including natural and social sciences, and the humanities, can support ambitious nitrous oxide abatement by focusing on several key gaps in the existing knowledge base.

6.3.1. Measurement across scales and methods

More accurate measurements of nitrous oxide emissions, especially from agriculture, are key. This requires improvements across different spatial and temporal scales in terms of instrumentation, from flux measurements to satellite measurements, to better constrain nitrous oxide emission totals and their seasonal variations. More granular activity data, such as fertiliser consumption and livestock numbers, especially in developing countries, would also enhance efforts to better quantify and abate nitrous oxide emissions. Better measurement and reporting of nitrous oxide emissions from all other sectors, including nitric and adipic production, would also greatly benefit the development and implementation of effective abatement measures.

6.3.2. Modelling

There are several areas for which modelling of nitrous oxide emissions, sources and impacts could be improved from including gender in disaggregated health impact related to air pollution and ozone depletion, to the ability to simulate more transformative change, to better capturing the seasonality of agricultural nitrous oxide emissions and the subsequent effectiveness of different abatement measures. In certain cases, this requires a more detailed scientific understanding and parameterisation of the processes driving nitrous oxide emissions. Enhanced modelling could enable countries to develop more accurate national emissions estimates and thereby improve national reporting to international bodies such as the UNFCCC.

6.3.3. Nitrogen and implications of decarbonisation

A better understanding of the nitrogen and nitrous oxide implications of different decarbonisation measures and policies is needed, including the use of ammonia as a marine shipping fuel, incentives for bioenergy production and soil carbon sequestration efforts, to minimise the trade-offs between carbon dioxide, methane and nitrous oxide abatement. Without it, there is a considerable risk that the greenhouse gas mitigation delivered by these measures and policies will be partially, or even completely, offset by increased nitrous oxide emissions.

6.3.4. Governance

Current policies to address nitrous oxide in agriculture have not led to meaningful emissions reductions. Involving other social science disciplines in the design and implementation of integrated nitrogen policies is key. Social scientists, for example, could provide insights on to how to better ensure the lasting adoption of abatement technologies and practices by farmers and integrate equity considerations into policy design; political economists could increase the understanding of the power dynamics that exist between actors across the agri-food system; while lawyers could advise on the design of specific governance options.

6.3.5. Innovation

Research and development of nitrous oxide abatement measures, especially in the agricultural sector, has been lacking. New technologies and practices that are adapted to specific crops, geographies, soil types, climates and growing cultures are crucial. Such innovation should come from both the public and private sector and maximise nitrous oxide abatement potential while minimising the risk of pollution swapping with other nitrogen compounds and other climate and air pollutants, such as methane.

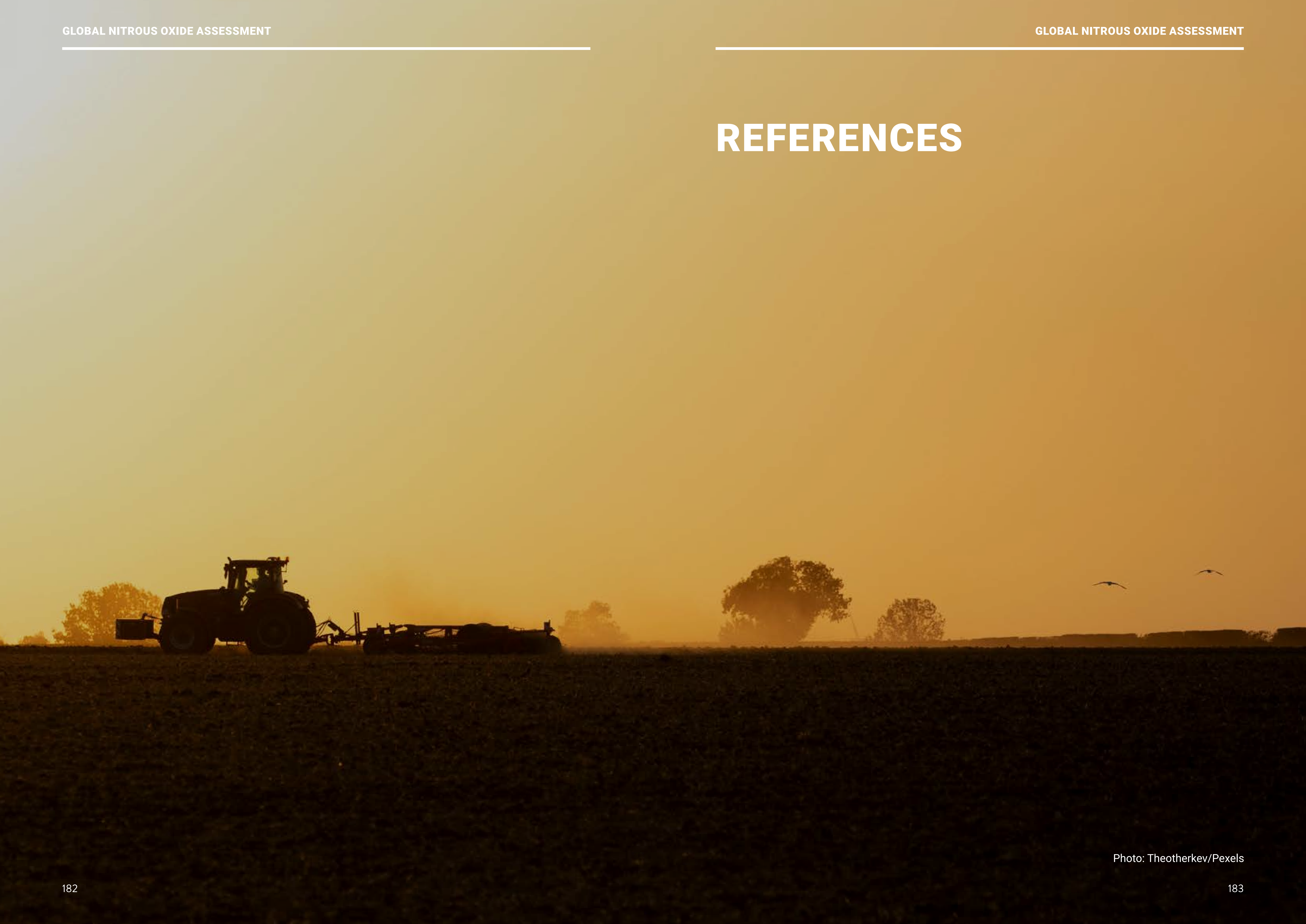
6.4 INTERNATIONAL POLICY OPTIONS FOR NITROUS OXIDE ACTION

Nitrous oxide's impacts on the ozone layer and climate, coupled with its close links to other nitrogen compounds, means that it falls under the remits of several international environmental agreements, including the Paris Climate Agreement and the Vienna Convention for the Protection of the Ozone Layer. Parties to these conventions could consider more focused action on nitrous oxide. While nitrous oxide is listed in many other NDCs as part of the broader basket of greenhouse gasses, including carbon dioxide, methane and hydrofluorocarbons, only one country, as far as the authors of this Assessment are aware, has included reduction targets specific to nitrous oxide.


Photo: Pixabay/Pexels

Under the Vienna Convention, several options are also available, including requesting a special report from the assessment panels under the Montreal Protocol to comprehensively evaluate the influence of nitrous oxide on the stratospheric ozone layer and the ensuing ecosystem impacts, as well as the technical and economic feasibility of abatement measures. In terms of policy action, the Montreal Protocol has experience in addressing both by-product emissions, trifluoromethane (HFC-23) from chloro-difluoromethane (HCFC-22) production, and the production and consumption of agrochemicals, the phase-out of methyl bromide. This experience could potentially be adapted to address nitrous oxide emissions from nitric and adipic acid production and agriculture, respectively.

Beyond these two conventions, there are other policy options and forums that could enable a sustainable nitrogen management approach to nitrous oxide abatement. Two recent nitrogen resolutions under the United Nations Environment Assembly (UNEA) and the establishment of a Nitrogen Working Group under UNEP have begun to encourage the development of national action plans on nitrogen. Target 7 under the recent post-2020 Global Biodiversity Framework calls for halving nutrient losses to the environment. The Task Force on Reactive Nitrogen, under CLRTAP, has published guidance on integrated approaches to nitrogen management for the implementation of ammonia and nitrogen oxides targets under the Gothenburg Protocol. Furthermore, implementation of several of the SDGs, from ending hunger (SDG 2), to ensuring clean water and sanitation (SDG 6), to climate action (SDG 13), could be enhanced by a sustainable nitrogen management approach as outlined in the forthcoming INA. In short, there are few actions that could deliver as many simultaneous environmental and human health benefits as a sustainable nitrogen management approach to nitrous oxide.



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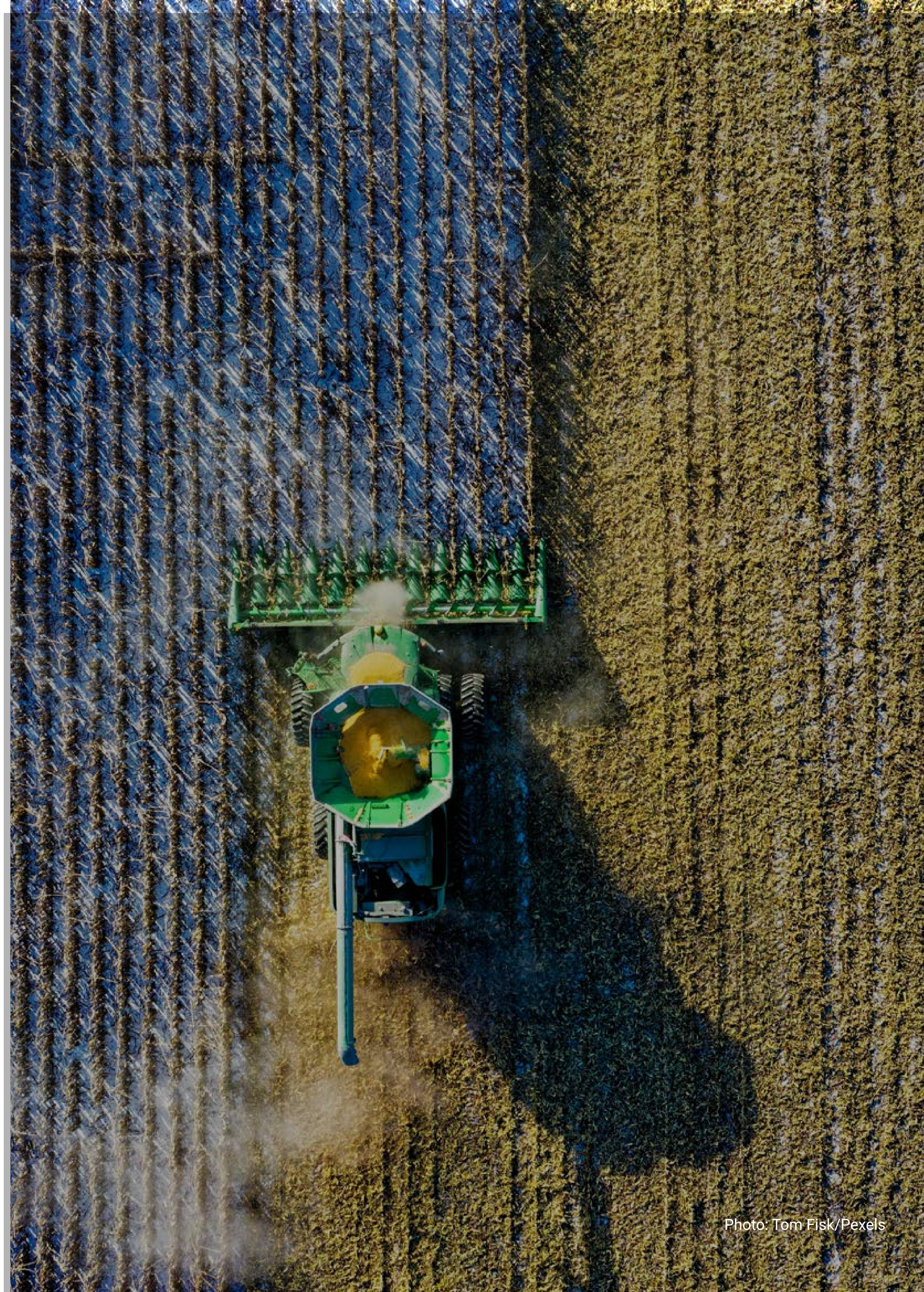
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GLOSSARY, ACRONYMS AND ABBREVIATIONS

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Aerosols – are collections of airborne solid or liquid particles with a typical size between 0.01 and 10 micrometres. 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.

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 per cent of the abundance of a chemical to be removed from the atmosphere in the absence of emissions.

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

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

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 (CO_2) that would have the same global warming ability, when measured over a specified timescale.

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 atmospheric nitrogen (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 (O_3) amounts. One DU is the number of molecules of O_3 that would be required to create a layer of pure O_3 0.01 millimetres 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-fertilisation of an aquatic ecosystem by inorganic nutrients (e.g. nitrates and phosphates). This may occur naturally or through human activity, such as from fertiliser runoff and sewage discharge. It typically promotes excessive growth of algae, which could result in the depletion of available dissolved oxygen.

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 (CO_2), the greenhouse gas that causes the greatest anthropogenic radiative forcing because of its overwhelming abundance, is chosen as the reference gas. Global warming potential (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 synthesises reactive nitrogen as ammonia (NH_3) from the reaction of nitrogen (N_2) and hydrogen (H_2).

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 (N) 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.

Megatonnes (Mt) – the units used in this report to describe emissions of nitrous oxide per year (Mt N_2O/yr). Equivalent to 1 million tonnes or 1 billion kilograms or 1 teragram grams.

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 nitrous oxide (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 ammonium (NH_4^+) to nitrogen dioxide (NO_2) which is then further oxidized to nitrates (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.

(Ozone-depleting substance ODS) – a substance that can deplete the stratospheric ozone layer and that is 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 trichlorofluoromethane (CFC-11), which has an ODP of 1.

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

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.

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

Stratospheric ozone depletion – depletion of ozone (O_3) in the stratosphere (the second layer of the atmosphere, located above the troposphere). This depletion allows increased levels of Ultraviolet B (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.

Super pollutant – a grouping of atmospheric pollutants that have climate effects greater than carbon dioxide (CO_2) and can have environmental and human health effects.

Synthetic fertiliser – fertiliser produced industrially.

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 (O_3) in the troposphere.

Urea – a reactive nitrogen form, urea (or carbamide) is an organic compound with the chemical formula $CO(NH_2)_2$. It is the main nitrogen-containing substance in the urine of mammals. Urea is widely used in fertilisers as a convenient source of nitrogen. It is also an important raw material for the chemical industry.

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.

ACS	American Cancer Society
ACS-CPS	American Cancer Society Cancer Prevention Study
AGAGE	Advanced Global Atmospheric Gases Experiment
AR5	Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change
AR6	Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change
BAF	biological amplification factor
BAU	business as usual
BCC	basal cell carcinoma
BECCS	bioenergy with carbon capture and storage
billion	10^9
BrO_x	bromines oxides
C	carbon
CAMS	Community for Analytical Measurement Science
CCl4	carbon tetrachloride
CCAC	Climate and Clean Air Coalition
CCCma	Canadian Centre for Climate Modelling and Analysis
CDR	carbon dioxide removal
CCMI	Chemistry-Climate Model Intercomparison
CDM	Clean Development Mechanism

CESM	Community Earth System Model
CFC	chlorofluorocarbon
CFC-11	trichlorofluoromethane
CFC-12	dichlorodifluoromethane
CH_4	methane
CI	confidence interval
ClO_x	chlorine oxides
CLM	Community Land Model
CLRTAP	Convention on Long Range Transboundary Air Pollution
CMAM	Canadian Middle Atmosphere Model
CMIP	Coupled Model Intercomparison Project
CMM	cutaneous malignant melanoma
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CRDS	cavity ring-down spectroscopy
DALY	disability-adjusted life years
DJF	December, January, February
DU	Dobson unit
EA	East Asia
EEF	enhanced-efficiency fertilizer

EF	emission factor
ENA	European Nitrogen Assessment
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
et al	and others *(et alia)*
ETS	emissions trading scheme
EU	European Union
EUR	euro
EV	electric vehicle
FAO	Food and Agriculture Organization of the United Nations
FSU	former Soviet Union
g	gram
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies model
GBD	Global Burden of Disease
GC	gas chromatographs
GCM	general circulation model
GDP	gross domestic product
GEEPA	Global Energy and Environmental Policy Analysis
GEMM	Global Exposure Mortality Model

GEOS	Goddard Earth Observing System
GSFC 2D	National Aeronautics and Space Administration Goddard Space Flight Center two-dimensional mode
Gg	gigagram (10^9 grams/1,000 tonnes)
GHG	greenhouse gas
GHOST	global hidden ozone structure
GISS	Goddard Institute for Space Studies
Gothenburg Protocol	Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone
GOSAT	greenhouse gases observing satellite
GSFC	Goddard Space Flight Center
Gt	gigatonne (10^9 tonnes)
GWP	global warming potential
H_2	Hydrogen
ha	hectare
HCFC	hydrochlorofluorocarbon
HCFC-22	chlorodifluoromethane
HFC	hydrofluorocarbons
HFC-23	trifluoromethane
HO_2	hydroperoxyl
HO_x	hydrogen oxides

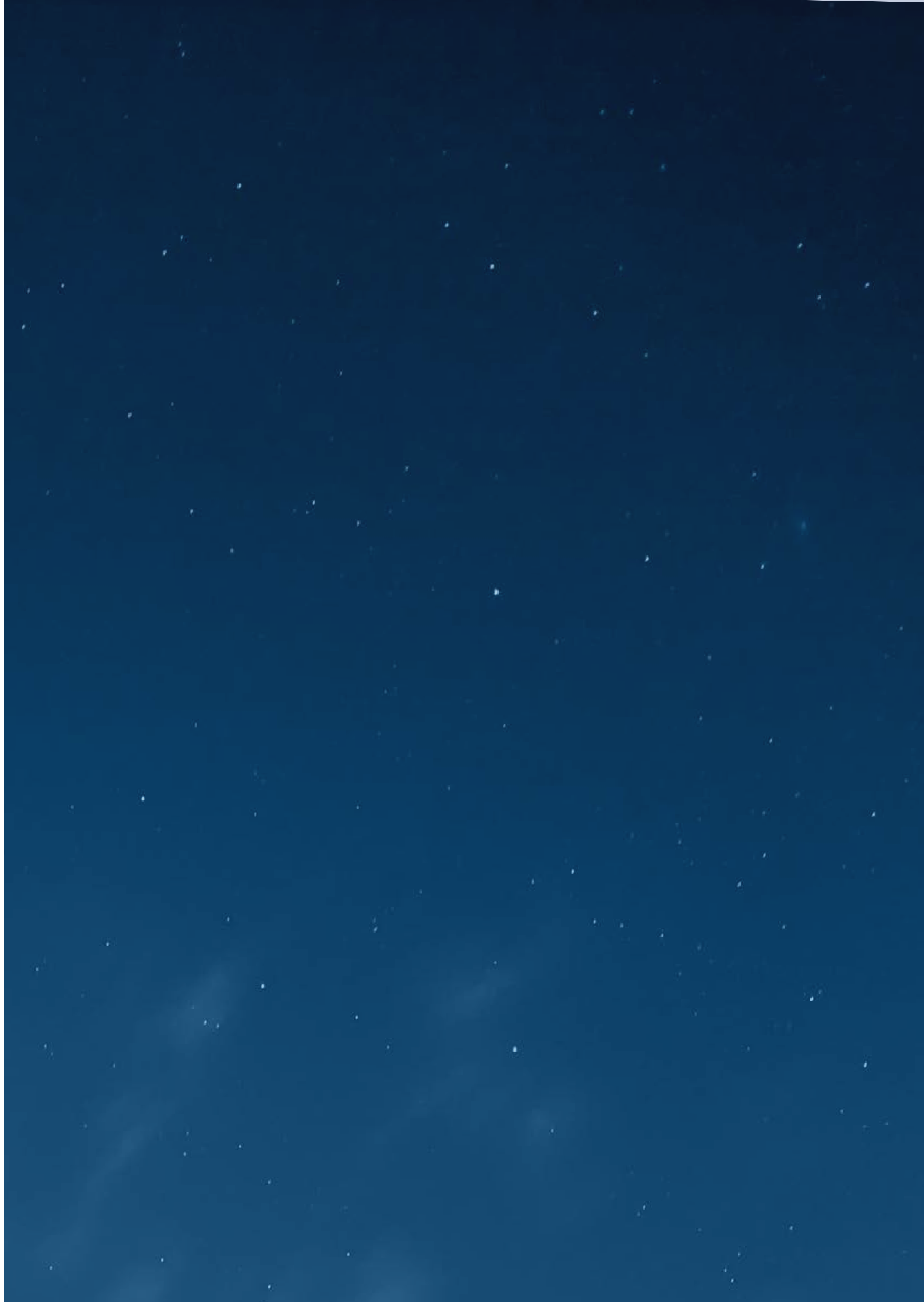
hPa	hectopascal
IAM	Integrated Assessment Model
IASI	infrared atmospheric sounder interferometer
ICOS	integrated cavity output spectroscopy
i.e.	that is *(id est)*
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMNS	Institute for Integrated Micro and Nano Systems
INA	International Nitrogen Assessment
IPCC	Intergovernmental Panel on Climate Change
JJA	June, July, August
JPL	Jet Propulsion Laboratory
kg	kilogram
km	kilometre
kt	kilotonne (1,000 tonnes)
m	metre
m^2	square metre
MACC	marginal abatement cost curves
MAM	modal aerosol microphysics
MENA	Middle East and North Africa

Metop	meteorological operational (satellite)
mm	millimetre
Montreal Protocol	Montreal Protocol on Substances that Deplete the Ozone Layer
Mt	megatonne (10^6 tonnes)
Mt/yr	megatonnes per year
N	nitrogen
N_2	molecular nitrogen
NASA	National Aeronautics and Space Administration
NDC	nationally determined contribution
NH_3	ammonia
NH_4^+	ammonium
nm	nanometre (10^{-9} metres)
NMB	Normalized Mean Bias
NO	nitric oxide
NOAA	National Oceanic and Atmospheric Administration
N_2O	nitrous oxide
NO_2	nitrogen dioxide
NO_3^-	nitrate
NO_x	nitrogen oxides

NUE	nitrogen-use efficiency
O	oxygen (a free oxygen atom)
O_2	oxygen (two oxygen atoms chemically bound to form an oxygen molecule)
O_3	ozone
O_x	Oxides
ODS	ozone-depleting substance
OECD	Organisation for Economic Co-operation and Development
OH	hydroxide
P	phosphorus
pH	acidity (potential of hydrogen)
PM	particulate matter
$PM_{2.5}$	fine particulate matter with a diameter of 2.5 micrometres or less
PM_{10}	particulate matter with a diameter of 10 micrometres or less
POLES	Prospective Outlook on Long-term Energy Systems
ppb	parts per billion
ppbv	parts per billion by volume
ppmv	parts per million by volume
PSC	polar stratospheric cloud

QCLAS	quantum cascade laser absorption spectrometry
RAF	radiation amplification factor
RCP	representative concentration pathway
REMIND	Regional Model of Investment and Development
RF	radiative forcing
R&D	research and development
SCC	squamous cell carcinoma
SCR	selective catalytic reduction
SCUP-h	Skin Cancer Utrecht Philadelphia
SDG	Sustainable Development Goals
SLCF	short-lived climate forcer
SSA	Sub-Saharan Africa
SSP	shared socioeconomic pathway
t	tonne
TANSO	thermal and near infrared sensor for carbon observation
Tg	teragram (10^{12} grams/1 million tonnes)
TOC	total ozone column
TUV	tropospheric ultraviolet and visible (radiation model)
UN	United Nations
UNEA	United Nations Environment Assembly

UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
USD	United States dollar
USDA	United States Department of Agriculture
USSR	Union of Soviet Socialist Republics
UV	ultraviolet
VRT	variable rate technology
W	watt
WACCM	Whole Atmosphere Community Climate Model
WMO	World Meteorological Organization
WWTP	wastewater treatment plant
yr	year
2D	two dimensional
°C	degrees Celsius



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