A Primer on Anthropogenic Nitrous Oxide:

The Last Significant Ozone-Depleting Substance and Greenhouse Gas Not Regulated by the Montreal Protocol

3 September 2025

Institute for Governance & Sustainable Development

Suggested citation
Institute for Governance & Sustainable Development (2025). A PRIMER ON ANTHROPOGENIC NITROUS OXIDE (N_2O): THE LAST SIGNIFICANT OZONE-DEPLETING SUBSTANCE AND GREENHOUSE GAS NOT REGULATED BY THE MONTREAL PROTOCOL.

Contributing authors
Valerie Fajardo,* Durwood Zaelke, Alyssa Hull, Gabrielle Dreyfus, Xiaopu Sun, Richard "Tad" Ferris, and Julie Miller

Acknowledgments
We thank Laura Bloomer, Sean Dennis, Ana María Kleymeyer, David Kanter (International Nitrogen Initiative), Eric Davidson (University of Maryland), Xin Zhang (University of Maryland), Emilio Rodriguez (GIZ), Kamilla von Reden (GIZ), and other readers for comments that allow us to continue to update and improve this *Primer*.

* Climate & Environmental Law Fellow at the University of Miami School of Law, as of September 2024.

About the Institute for Governance & Sustainable Development

IGSD's mission is to ensure fast cuts to the non-carbon dioxide climate pollutants and promote other fast climate mitigation strategies to slow near-term global warming and self-amplifying climate feedbacks, avoid or at least delay catastrophic climate and adverse societal tipping points, and limit global temperature to 1.5 °C—or at least keep this temperature guardrail in sight, limit overshoot, and return to a safe temperature as fast as possible.

IGSD's research confirms that decarbonization alone is insufficient to slow near-term warming to keep us below 1.5 °C or even the more dangerous 2 °C guardrail. The fastest and most effective strategy is to combine the marathon to zero out carbon dioxide (CO_2) emissions from decarbonizing the energy system *with* the sprint to rapidly cut non-CO_2 super climate pollutants and protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH_4), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O).

Combining the fast mitigation sprint with the decarbonization marathon also helps address the ethical issues of intra-generational equity by giving societies urgently needed time to build resilience and adapt to unavoidable changes. The latest science suggests that the window for exceeding the 1.5 °C guardrail could close as soon as the early 2030s, making this the decisive decade for fast action to slow warming.

The fastest way to reduce near-term warming in the next two decades is to cut SLCPs. Because they only last in the atmosphere from days to 15 years, reducing SCLPs will prevent most of their predicted warming within a decade. Strategies targeting SLCP reductions can avoid four times more warming at 2050 than targeting CO_2 alone. Reducing HFCs can avoid nearly 0.1 °C of warming by 2050 and up to 0.5 °C by the end of the century. The initial HFC phasedown schedule in the Kigali Amendment to the Montreal Protocol will capture about 90 percent of this. Parallel efforts to enhance energy efficiency of air conditioners and other cooling appliances during the HFC phasedown can double the climate benefits at 2050. Cutting methane emissions can avoid nearly 0.3 °C by the 2040s, with the potential for significant avoided warming from emerging technologies to remove atmospheric methane faster than the natural cycle.

Combining the fast mitigation sprint with the decarbonization marathon would reduce the rate of global warming by half from 2030 to 2050, slow the rate of warming a decade or two earlier than decarbonization alone, and make it possible for the world to keep the 1.5 °C guardrail in sight and limit overshoot. It would also reduce the rate of Arctic warming by two-thirds. This would help slow self-amplifying climate feedbacks in the Arctic and elsewhere and thus avoid or at least delay the cluster of projected tipping points lurking beyond 1.5 °C. Reducing climate risks and staying within the limits to adaptation are critical to building resilience.

IGSD's approach to fast mitigation includes science, technology, law and policy, and climate finance. IGSD works at the global, regional, national, and subnational levels.

Primer on Anthropogenic Nitrous Oxide (N_2O):
The Last Significant Ozone-Depleting Substance and Greenhouse Gas Not Regulated by the Montreal Protocol

Table of Contents

Figures and Tables

I. Executive Summary

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) and an ozone-depleting substance (ODS). Its global warming potential over 100 years (GWP_{100}) is 273 times greater than that of carbon dioxide (CO_2).[1] To slow self-amplifying feedbacks and avoid irreversible climate tipping points, the world must quickly cut global human-caused (anthropogenic) N_2O emissions as part of any fast climate mitigation strategy.[2] The term "radiative forcing" refers to changes in the balance of solar radiation entering the atmosphere and infrared radiation exiting as heat.[3] Current atmospheric concentrations of N_2O cause about 10% as much radiative forcing as CO_2,[4] making N_2O a significant contributor to climate change. The Intergovernmental Panel on Climate Change (IPCC) estimates that human-caused N_2O was responsible for approximately 0.1 °C of anthropogenic global surface temperature increase over 2010–2019 relative to pre-industrial levels.[5] Fast action on N_2O is essential for keeping warming within the Paris Agreement goals of well under 2 °C, while pursuing efforts to limit warming to 1.5 °C.[6]

Continuing emissions of N_2O could also delay full recovery of the stratospheric ozone layer[7] that protects Earth from the harmful effects of ultraviolet (UV) radiation. This delay would cause higher levels of UV exposure that can harm crops and contribute to global warming by damaging natural carbon sinks—oceans, forests, permafrost, and soils—that trap and hold CO_2.[8]

Because N_2O is the most significant ODS not yet regulated by the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol), there is a strong case for adding it to the treaty, at least to control industrial emissions. The most recent Quadrennial Assessment Report of the Montreal Protocol's Scientific Assessment Panel states that N_2O emissions have accelerated over the last 20 years and now exceed some of the highest projections.[9] Compared to CFC-11, commonly known as Freon-11, anthropogenic N_2O emissions between 2016 and 2020 were equal in ozone depletion to approximately 20% of CFC emissions in 1987, when CFC emissions peaked.[10] By 2050, ambitious reductions of anthropogenic N_2O emissions can provide approximately the same ozone benefits as the Montreal Protocol's accelerated phase-out of hydrofluorocarbons—and five times the benefits by 2100.[11]

Industrial N_2O emissions are by-products from manufacturing nitric and adipic acids and caprolactam. These point-source emissions can be cut immediately and are a logical starting point for reducing N_2O under the Montreal Protocol.[12] Ambitious abatement of industrial N_2O could avoid 2.5 billion tons of carbon dioxide equivalent emissions (CO_2e) and 160,000 tons of CFC-11 equivalent emissions.[13] Proven abatement technology at nitric and adipic acid production facilities could reduce projected industrial N_2O emissions by 86% by 2030.[14] This technology has reduced global N_2O emissions at some plants for decades at minimal costs,[15] and the Montreal Protocol could ensure that all plants operate with this technology. Such a global approach could build on the bilateral efforts of the United States and China, which account for over 80% of industrial N_2O emissions. These nations are taking steps "to cooperate on respective measures to manage N_2O emissions."[16]

The agriculture sector is responsible for 75% of anthropogenic N_2O emissions; agricultural N_2O emissions are projected to grow unless mitigation measures are implemented.[17] Improved fertilizer application, better manure management, and other mitigation measures could reduce these emissions by about 40 percent below current levels by 2050.[18] Montreal Protocol Parties have relevant experience from their decades-long effort to phase out the agricultural fumigant methyl bromide (MeBr) through the substitution of tested alternatives.[19]

Fertilizer management measures also benefit the environment and food security by reducing nitrogen pollution and its adverse effects on fisheries and other food sources.[20] Fertilizer management may also reduce costs and dependence on synthetic nitrogen (N) fertilizers that have supply chains easily disrupted by climate change and geopolitical conflict. Finally, to win political support for maximizing the environmental benefits of N_2O mitigation, it's critical to understand the impacts of mitigation measures on farmers.

Controls under the Montreal Protocol would lock in N_2O emissions reductions to protect the ozone layer and complement other control mechanisms. Global and regional treaties, governance bodies, and scientific initiatives have increased action on nitrogen pollution and could further advance fast mitigation of N_2O. 90% of countries already include N_2O emissions in the basket of gases covered by their Nationally Determined Contributions (NDCs),[21] opening the door for enhanced financial and technical support to cut N_2O. The Convention on Long-Range Transboundary Air Pollution—a regional air pollution convention among North America, Europe, Russia, and former Eastern Bloc countries—is seeking to address sources of the air pollutant ammonia (NH_3). Reducing NH_3 sources could result in N_2O mitigation as a co-benefit.[22] This and other global initiatives, including the work of the United Nations Environment Programme (UNEP) Nitrogen Working Group, need to be strengthened to reduce N_2O emissions.

While mitigation technology and global attention to N_2O are improving, more action is needed to accelerate N_2O mitigation. This *N_2O Primer* provides background for a global campaign to reduce N_2O emissions. The *Primer* explains the anthropogenic sources of N_2O, explains the benefits of reducing N_2O emissions, describes the available cost-effective methods to cut N_2O emissions, provides an overview of global governance regimes and initiatives that address N_2O, and offers suggestions for strengthening global governance.

II. N_2O is the last significant ozone-depleting substance and climate pollutant not controlled by the Montreal Protocol.

Nitrous oxide (N_2O) is a colorless gas familiar to many people as "laughing gas" and for its use as an anesthetic. Since the 1970s, scientists have warned that N_2O emissions from agriculture—especially from the use of nitrogen fertilizer—damage the stratospheric ozone layer that protects life on Earth from harmful ultraviolet (UV) radiation. By 1980, researchers had shown that N_2O is a greenhouse gas (GHG) strongly contributing to global warming.[23]

Emissions of N_2O occur both naturally and through human-caused (anthropogenic) sources. Natural sources include forests and the oceans; in the nitrogen cycle, bacteria in soil or water break down nitrogen into different forms, making it available for plants and animals. Natural sources account for about 65% of all N_2O emissions. Anthropogenic sources include agriculture, chemical manufacturing, and burning fossil fuels. These human activities currently comprise 35% of total N_2O emissions.[24]

Studies of ice cores show that atmospheric N_2O concentrations were stable for roughly 2,000 years but have rapidly increased since 1850.[25] Increased atmospheric N_2O is a direct outcome of increased N_2O emissions.

Despite warnings from the scientific community, global N_2O emissions rose by 40% from 1980 to 2020.[26] Direct emissions from nitrogen (N) additions in agriculture were the single largest source of increase. Indirect emissions, including from bacterial activity on fertilizer runoff and from the liberation and redeposition of ammonia (NH_3) and nitrogen oxides to soil, are also increasing.[27] Natural emissions from land and oceans have remained relatively stable.[28]

Global N_2O emissions are increasing.

Global anthropogenic N_2O emissions accounted for roughly 35% of total N_2O emissions between 2010 and 2019.[29] In 2020, anthropogenic N_2O emissions rose to approximately 3.1 gigatons of carbon dioxide equivalent ($GtCO_2e$).[30] This roughly equals the GHG emissions from over 735 million gasoline-powered cars for one year.[31]

The breakdown of anthropogenic N_2O emissions includes:[32]

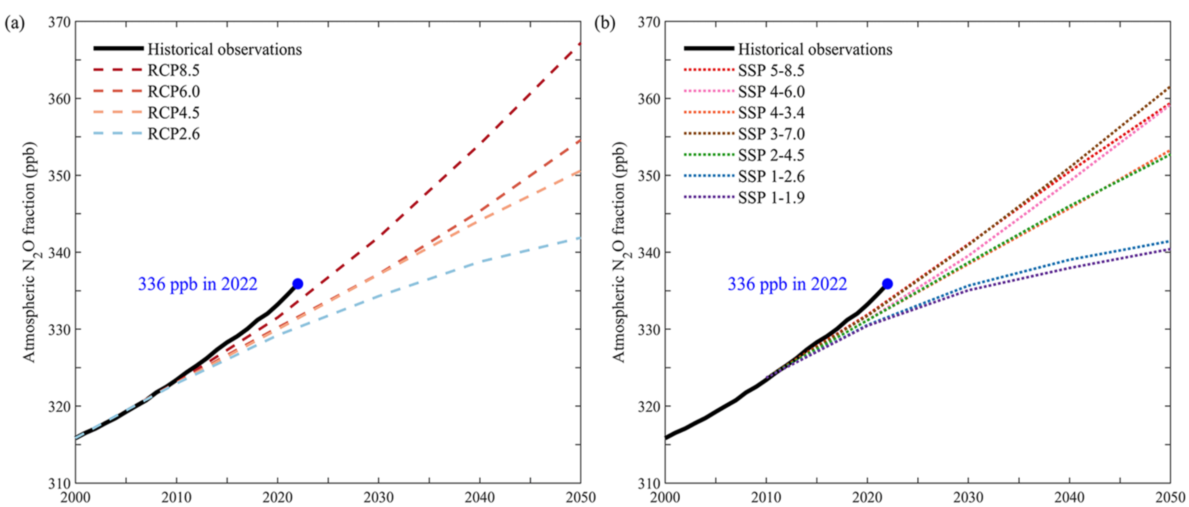
- Approximately 75% from direct and indirect agricultural emissions
- Approximately 5% from industry
- Approximately 20% from biomass burning, fossil fuel combustion, wastewater treatment, aquaculture, biomass burning, and other sources

Note: See Appendix C for more information on GWP calculations.

Atmospheric N_2O concentrations are increasing.

Atmospheric concentrations of N_2O reached over 337 parts per billion (ppb) in 2024, a 25% increase from pre-industrial levels that exceeds the most pessimistic projections of the IPCC (figure 2).[33]

Figure 1. Historical atmospheric N_2O concentrations compared to IPCC projections



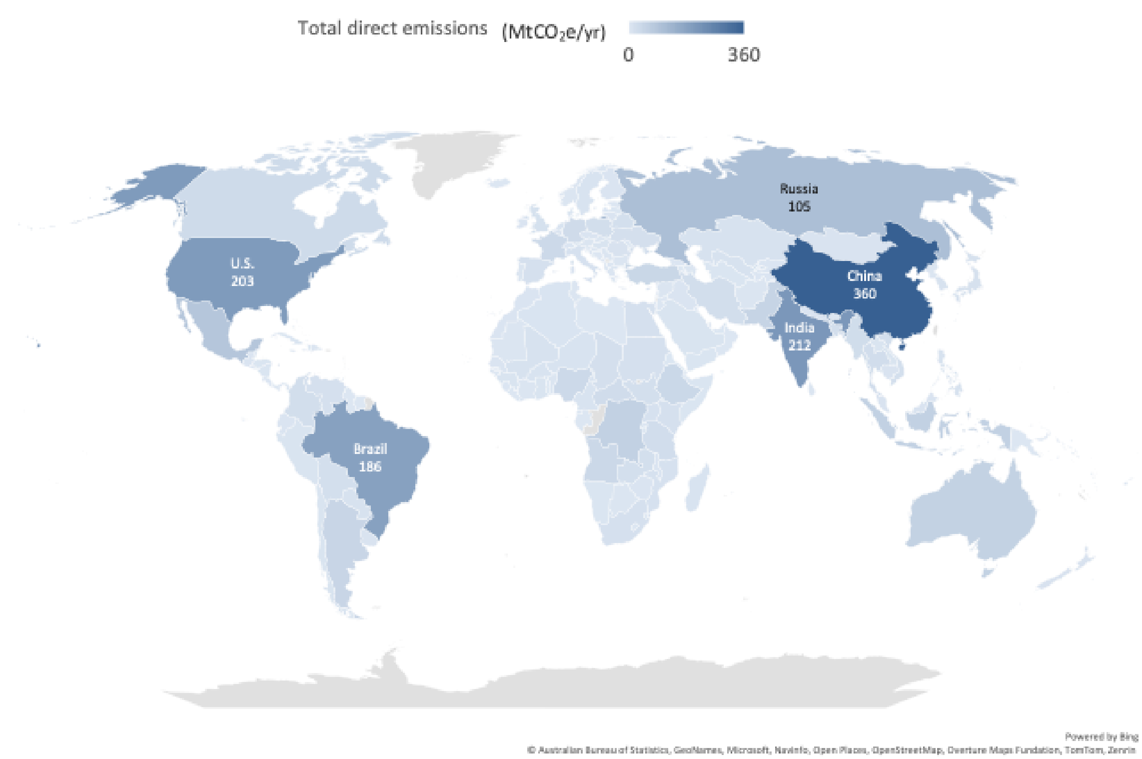
N_2O concentrations (blue dot) are greater than all projected scenarios in (a) the Representative Concentration Pathways (RCP) in the IPCC Fifth Assessment Report and (b) the Socioeconomic Pathways in Coupled Model Intercomparison Project Phase 6 (CMIP6). See Tian H., et al. (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENTIFIC DATA 16: 2543–2604, 2559.

Five countries are responsible for approximately 50% of anthropogenic N_2O emissions.

According to the Global Carbon Atlas, the following countries were the largest sources of direct anthropogenic N_2O emissions in 2020:

- China (14%)
- Brazil (11%)
- U.S. (10%)
- India (10%)
- Russia (7%)

Figure 2. Direct anthropogenic N_2O emissions by country in 2020



Direct anthropogenic N_2O emissions in metric million tons of CO_2e/yr. The top five emitting countries are labelled on the map. Taken together, the EU accounts for emissions of approximately 196 $MtCO_2e$/yr (~8% of global emissions). Source: Global Carbon Atlas.

From the 1980s to the 2010s, overall European N_2O emissions decreased by 31% primarily due to reductions in fossil fuel use, industry emissions, waste and wastewater emissions, and biomass burning.[34] Agricultural emissions also decreased during this time frame, mainly because of less fertilizer use after the breakup of the Soviet Union, but this decrease levelled off by the 2000s.[35]

China's N_2O emissions have been increasing in all sectors, with agriculture the largest contributor.[36] The growth in China's anthropogenic N_2O emissions accounted for 40% of the total global increase from 1980 to 2020.[37]

III. Cutting N_2O emissions helps heal the ozone layer, delays reaching irreversible climate tipping points, and provides numerous health and environmental equity benefits.

Cutting N_2O helps ozone layer recovery because N_2O is an ODS.

N_2O is the main source of nitrogen oxides in the stratosphere, which destroy the ozone layer.[38] Reducing N_2O emissions is vital to maintaining the progress achieved by the Montreal Protocol since 1987 in repairing the stratospheric ozone layer. When compared to CFC-11, also known as Freon-11, anthropogenic N_2O emissions between 2016 and 2020 were estimated to have twice the ozone-depleting potential of all CFC emissions in 2020. N_2O emissions in this time span were also equal in ozone depletion to approximately 20% of CFC emissions in 1987, when these emissions were at their peak.[39]

It is important to note that avoiding trade-offs between ozone depletion and climate change will require reducing CO_2, N_2O, and methane at least to levels consistent with climate scenarios having low to moderate future GHG emissions.[40] Mitigation strategies targeting agricultural N_2O emissions will not hinder ozone goals and are necessary to meet climate goals.[41]

Cutting N_2O limits global warming directly because N_2O is a GHG.

N_2O is a climate pollutant with a GWP_{100} of 273; over a 100-year span, a unit of N_2O has 273 times the ability to cause global warming than the same mass of CO_2. The GWP_{20} of N_2O is also 273, because N_2O has an atmospheric lifetime of 109 years.[42] (see Appendix C for more information about calculations of GWP). Ambitious reductions in N_2O emissions could avoid the equivalent of up to 235 billion tons of CO_2 by 2100. When paired with associated livestock methane mitigation, reducing N_2O emissions could reduce warming later this century by 0.1 °C as compared to additional warming of 0.2 °C if additional action is not taken.[43]

Fast cuts to emissions of N_2O and other climate super pollutants, such as methane, hydrofluorocarbons (HFCs), black carbon, and tropospheric ozone, are needed to keep the 1.5 °C long-term temperature guardrail of the Paris Agreement in sight. The IPCC Sixth Assessment Group (AR6), Working Group III stated that substantial reductions to N_2O and the other super pollutants are required by 2030 to limit warming to a 1.5 °C or even a 2 °C target.[44] Not exceeding these temperature guardrails is essential to limit the risk of passing dangerous climate tipping points, including:

- Collapse of the Atlantic Meridional Overturning Circulation, the system of ocean currents that transport warmer water north at the surface and cooler water south at depth
- Collapse of the Greenland and West Antarctic ice sheets
- Dying back of the Amazon rainforest and boreal forests
- Collapse of Arctic summer sea ice
- Die off of warm-water coral reefs, seagrass meadows, and mangroves[45]

The consequences of reaching any of these tipping points would be far-reaching and likely irreversible.

Today's rapidly warming world risks triggering self-amplifying feedbacks that would increase natural N_2O emissions, a vicious cycle that fuels additional warming. For example, in northern latitudes, warming of pristine wetlands increases these wetlands' N_2O emissions by 19% due to increased nitrogen mineralization, which is the conversion of nitrogen to inorganic mineral forms.[46]

This same nitrogen mineralization process also occurs in thawing permafrost regions, especially in the Arctic.[47] A quarter of the Arctic has a high probability of emitting N_2O in the event of permafrost thaw.[48] Years after thawing—as soil drainage improves and nitrifying and denitrifying microbial communities begin to form—re-vegetation of permafrost soils can increase N_2O emissions.[49] In addition to emitting N_2O,[50] thawing permafrost releases CO_2 and methane,[51] which could lock in additional global warming of 0.05–0.7 °C by the end of the century.[52] Higher air and surface soil temperatures can increase N_2O emissions in subarctic and alpine peatlands by up to 460%.[53] Note that even at today's level of warming, abrupt, localized permafrost thaw is already occurring.[54]

Finally, if anthropogenic N_2O emissions remain at their current levels without significant reductions, limiting global warming to the 1.5 °C target will require larger and more expensive cuts to CO_2 and methane.[55]

Excess reactive nitrogen from fertilizer generates N_2O.

Agricultural N_2O emissions are a form of nitrogen pollution resulting from too much reactive nitrogen (N_r) in the environment. When an excess of nutrients essential for plant growth—primarily nitrogen and phosphorus—accumulates in water, eutrophication occurs. During eutrophication, algae flourishes until the water's surface is covered with algal blooms, then as bacteria decompose dead algae, a hypoxic environment is created.[56] Schulz, *et al.* (2023) found increased N_2O emissions in estuaries due to eutrophication and elevated levels of crop nutrients.[57]

However, N_r can have complex climate effects that, in some cases, create a temporary decrease in warming:

- Fertilizer application and deposition of atmospheric N_r can increase drawdown and storage of CO_2 in land or the oceans, which could decrease warming.[58]
- Excess N_r can also lead to the formation of air pollutants like nitrogen oxides (NO_x) and ammonia (NH_3). These pollutants can act to cool the atmosphere in two ways:
    - First, NO_x and NH_3 can react in the atmosphere to form cooling aerosols that reflect sunlight.[59] These cooling aerosols currently conceal or "mask" the extent of global warming.[60]
    - Second, NO_x emissions shorten the atmospheric lifetimes of other climate super pollutants, such as methane.[61] This can also produce an indirect cooling effect.[62]

Masking and unmasking effects

Cooling aerosols reflect solar energy back into space, cooling the atmosphere and masking the full extent of global warming. Reducing these cooling aerosols reveals or "unmasks" warming caused by the heat-trapping greenhouse gas blanket around the planet.

The major source of NO_x is the combustion of fossil fuels. Decarbonization policies that include phasing out fossil fuels will create some unmasking effects by reducing NO_x. This effect is very short-lived and disappears from the atmosphere in a matter of hours to days.[63] The unmasking effect also applies to measures targeting fertilizer use.

Unmasking in no way negates the urgency of cutting N_2O, particularly given the many benefits of reductions as described in this *Primer*. Instead, unmasking highlights the need for fast, coordinated action on all climate super pollutants and CO_2.[64] Targeted measures to reduce N_2O from the agricultural and industrial sectors, such as improved nitrogen use efficiency and abatement of industrial N_2O, will result in net avoided warming.[65] Abating industrial N_2O emissions has net climate benefits over all timescales.[66]

Healing the ozone layer helps limit global warming by preventing UV damage to carbon sinks.

As discussed previously, the Montreal Protocol has helped repair the stratospheric ozone layer, and fast cuts to N_2O are needed to maintain the path to full ozone recovery. Stratospheric ozone protects the Earth's carbon sinks— oceans, forests, permafrost, and soils—from damage by UV radiation. If full ozone recovery is delayed, the ability of carbon sinks to hold and retain CO_2 will be compromised, meaning a greater risk of reaching irreversible climate tipping points.

Cutting N_2O reduces air, land, and water pollution.

Nitrogen pollutants formed from N_r impact air quality as well as terrestrial and aquatic ecosystems. NO_x is a major precursor of tropospheric ozone,[67] a climate and air pollutant with known adverse impacts on human respiratory health and crops.[68] Globally, from 400,000 to 1 million premature deaths[69] and at least 9 million asthma-related emergency room visits[70] each year can be attributed to ozone pollution. NH_3 is a precursor to fine particulate matter ($PM_{2.5}$) and contributes to acidification, eutrophication, and biodiversity loss in natural ecosystems.[71] $PM_{2.5}$ is also an air pollutant: from three to nine million premature human deaths annually can be attributed to $PM_{2.5}$ exposure.[72]

In addition, on land, excess N_r encourages the growth of nitrogen-loving plant species that outcompete other species and reduce biodiversity.[73] In water, eutrophication kills fish and other aquatic life.[74]

In short, controlling nitrogen pollution from agricultural operations could reduce N_2O, NO_x, and NH_3 emissions and deliver environmental and public health co-benefits.

Improved agricultural fertilizer practices and processes benefit global food security while reducing N_2O emissions.

Optimizing N fertilizer use contributes to global food security. The rise in fuel prices and cutbacks in ammonia production have increased the cost of fertilizer production.[75] In 2021, China—one of the largest fertilizer-producing countries—reduced fertilizer exports to mitigate rising raw materials costs and address domestic food security concerns.[76] The export cutbacks negatively affected China's main buyers, like India, Pakistan, and Southeast Asia.[77]

Geopolitical instability caused by the Russian invasion of Ukraine also contributes to the global fertilizer shortage; Russia and Ukraine collectively export 28% of global nitrogen, phosphorous, and potassium fertilizers.[78] Fertilizer prices in the first six months of 2022 increased by nearly 30%, following a surge of 80% in 2021.[79] Improved agriculture practices that improve nitrogen use efficiency, especially in areas that already suffer from fertilizer overapplication, may relieve some of the strain caused by geopolitical instability and result in positive co-benefits for food security.

Reducing N_2O emissions provides socioeconomic benefits.

Nitrogen pollution results in significant socioeconomic costs.[80] The United States Environmental Protection Agency (U.S. EPA) estimates the social cost of N_2O at US$ 35,000–87,000 per ton of N_2O in 2020 and US$ 95,000–180,000 per ton of N_2O in 2080.[81] The social cost of a GHG is the monetary value of the net harm to society caused by every ton emitted into the atmosphere for all years. It accounts for all future impacts, including those on net agricultural productivity, human health, and property damage from increased flood risks and from changes in the frequency and magnitude of natural disasters.

Implementing nitrogen fertilizer reduction policies can result in a net benefit of US$ 377 million/yr through avoiding environmental pollution and not harming human health.[82] These fertilizer reduction policies can also encourage the development of better nitrogen management policies.[83] However, care must be taken with fertilizer controls to avoid creating trade-offs with food security, particularly in countries suffering from high food prices.

A study by Gu B., *et al.* (2023) estimated the global costs of 11 nitrogen-reducing measures in croplands to be in the range of US$ 14 billion to 24 billion in 2015 (~US$ 14 per hectare). The estimated net economic benefit to society in terms of crop yield, human health, ecosystems, and climate change is from US$ 353 billion to 599 billion—up to 25 times greater than the implementation cost. Roughly 43% of this economic benefit is from increased yields. This is especially important in the Middle East and Sub-Saharan Africa, where underutilization of nitrogen fertilizers results in low yields, and in India and China, where overuse of N fertilizers reduces yields.[84]

IV. The primary sources of N_2O emissions are industry, agriculture, and burning fossil fuels.

Industrial sources of N_2O emissions include adipic acid, nitric acid, and caprolactam production facilities.

As of 2021, the production of three chemicals accounts for essentially all industrial global N_2O emissions:

- 75% from adipic acid manufacturing
- 20% from nitric acid manufacturing
- 5% from caprolactam manufacturing[85]

Together, these emissions are the equivalent of the annual GHG emissions from approximately 44 coal-fired power plants.

Adipic acid is a raw material for nylon 6.6, coatings, plastics, urethane foams, elastomers, and synthetic lubricants.[86] The global nylon 6.6 market is the main consumer of adipic acid. In 2021, nylon 6.6 sales reached approximately US$ 5.25 billion/yr, with the automotive industry accounting for more than half of the market.[87] Adipic acid demand is expected to grow 87% from 2015 to 2030.[88]

Estimates of the number of operational adipic acid plants range from 21 to 39.[89] China hosts 11 plants[90] while the U.S. hosts 2.[91] Together, both countries account for about two-thirds of global adipic acid production.[92] The other adipic acid plants are in Brazil, France, Germany, Japan, Italy, and South Korea.[93]

Between 2010 and 2015, N_2O emissions increased by 27% due to the increase in adipic acid production in China from plants that operate without abatement technology.[94] These 11 Chinese facilities produce nearly half of the world's adipic acid, emitting N_2O at levels equal to the GHG emissions of approximately 25 million cars.[95]

Nitric acid is used as feedstock for ammonium nitrate and other nitrate-based fertilizers. The demand for nitric acid is expected to rise, driven by increases in fertilizer demand.[96] Based on 2015 levels, N_2O emissions from nitric acid plants are projected to increase 17% by 2030 if no abatement technology is implemented.[97] Davidson & Winiwarter (2023) found that only 100 out of the 580 nitric acid production plants worldwide abate their N_2O emissions.[98] The U.S., Russia, China, and Australia are leading emitters of N_2O via nitric acid production.[99]

Caprolactam, which is used to create synthetic fibers, also produces significant emissions of N_2O.[100]

While most nylon manufacturers have installed abatement technology to address adipic acid, nitric acid manufacturers are slow to follow suit.[101] Unabated emissions from nitric acid manufacturing can negate the benefits gained from abating emissions of all adipic acid and caprolactam manufacturers.[102]

Crop and livestock farming systems generate N_2O emissions from inefficient nitrogen management.

Agriculture is the main anthropogenic driver for increases in atmospheric N_2O concentration.[103] Fertilizer application is responsible for major increases in direct soil N_2O emissions in agricultural operations.[104] Crops do not efficiently use nitrogen,[105] leaving around 50% for bacteria in the soil to convert into N_2O or other N species.[106] A meta-analysis found that the increase in N_2O emissions is exponentially related to the amount of nitrogen fertilizer applied.[107]

Livestock and poultry production also emits N_2O. Livestock animals excrete 70–90% of the nitrogen in feeds through their urine and manure, which may be stored as dung or slurry for later use as organic fertilizer or simply left on pasture after grazing.[108] The excess N compounds from dung or slurry on soils undergo nitrification and denitrification, producing N_2O in the same way as for synthetic nitrogen fertilizer. Manure storage also produces N_2O when excess nitrogen undergoes denitrification under anaerobic conditions.[109]

Excess nitrogen leaching into soil results in indirect emissions from inland and coastal waters and atmospheric nitrogen deposition on land and in the ocean.[110]

Note that better manure management practices can provide additional climate and health benefits. Proteins and organic matter in manure from ruminant species (*e.g.,* cattle) decompose anaerobically to form methane.[111] Global estimates show that methane from ruminant manure comprises approximately 6% of total anthropogenic methane emissions.[112] The decomposition of animal waste, whether stored or applied to soils, produces ammonia (NH_3), an air pollutant.[113]

Fossil fuel combustion emits N_2O, and the obvious strategy is to stop burning fossil fuel.

Stationary combustion sources include coal-burning, oil-burning, and gas-powered plants. Mobile combustion sources include on-road vehicles, boats, and other craft. All produce N_2O as by-products[114] when fuels are burned at elevated temperatures.[115] Smokestack and tailpipe abatement options are limited because flue-gas N_2O concentrations tend to be low.[116] To significantly reduce N_2O emissions from fossil fuels, the most effective strategy is to stop burning fossil fuels.[117]

Biofuels are not necessarily a more climate-friendly solution.

Fossil fuel alternatives should be studied carefully to avoid creating trade-offs between CO_2 and N_2O emissions.[118] Biodiesel is created from vegetable oils or other biomass. Compared to the year 2000, biodiesel production is expected to result in a 40–67% increase in N_2O emissions from synthetic N fertilizer used on vegetable oil crops.[119] Several life-cycle assessments (LCAs) show that biofuel production may contribute to global warming through land use conversion.[120] Additionally, harvesting agricultural and forest residues to produce second-generation biofuels (fuels from non-food biomass) reduces sequestered carbon and increases GHG emissions.[121] This means that bioenergy with carbon capture and storage (BECCS) may not be a solution for CO_2 emissions that are difficult to abate.[122]

The combustion of ammonia from hydrogen gas (H_2), which is being investigated as an energy alternative,[123] also produces N_2O and other nitrogen pollutants.[124] Up to 5% of the nitrogen in ammonia can be lost in the atmosphere as nitrogen pollutants.[125] If ammonia use increases to meet future energy demands, the impact of the nitrogen released into the atmosphere from ammonia production could equal 50% of the impact from nitrogen fertilizer use.[126] At this rate of ammonia production, the resulting N_2O emissions would be equal to approximately 20 times the current level of industrial emissions and would make ammonia fuel the leading cause of ozone depletion.[127] In short, developing and adopting fossil fuel alternatives requires care and forethought.

Wastewater treatment generates N_2O, but the outcomes are variable and require more study.

Biological processes in wastewater treatment are responsible for most wastewater treatment N_2O emissions.[128] Mitigation measures such as process optimization and aeration control are available,[129] but their effectiveness is highly variable[130] and require further study.[131] Mitigation strategies should be explored on a case-to-case basis.

V. Cost-effective and easy-to-implement strategies for fast cuts to industrial and agricultural emissions already exist.

This *Primer* focuses on measures beyond fossil fuel decarbonization that can be quickly deployed to reduce N_2O emissions, have net avoided warming benefits, and make the most significant impact.

Cost-effective N_2O emission reduction technologies are ready to implement.[132] By 2050, N_2O emissions can potentially be reduced by 1.52 $GtCO_2e$, based on current technologies and costs.[133] Based on an earlier analysis, the breakdown of these emissions reductions is as follows:

- Approximately 57% from improved agricultural practices, including:
    - ~30% from improved manure management (0.49 $GtCO_2e$)
    - ~27% from optimizing fertilizer use (0.45 $GtCO_2e$)
- Approximately 36% from reduced industrial emissions (0.6 $GtCO_2e$)[134]

By 2100, up to 2.13 $GtCO_2e$ of anthropogenic N_2O emissions can be avoided—the equivalent of 6 years of current CO_2 emissions from burning fossil fuels.[135]

As shown in Table 1, the highest percentage of emissions reductions with the lowest margin costs are mitigations for industry.

Table 1. Overview of N_2O Emission Abatement Technology and Associated Marginal Costs

Source	Abatement Technology	Emissions Reductions	Marginal Costs (US$/$tCO_2e$)
Fertilizer application	Variable rate technology	19–24%	6–104
	Nitrification inhibitors	34–38%	56–112
	Precision farming	36–40%	860–1776
Adipic acid production	Catalytic or thermal reduction	95%	0.22
	Twin reduction device technology	99%	4.42
Nitric acid and caprolactam production	Catalytic or thermal reduction	80%	0.66
	Best available technology	94%	0.55

Source: Winiwarter W., et al. (2018). Technical Opportunities to Reduce Global Anthropogenic Emissions of Nitrous Oxide, Envtl. Res. Letters, 13:1–12, 3, tbl. 1

Dreyfus *et al*. (2022) showed that decarbonization strategies targeting fossil fuel phaseout, while necessary, are not sufficient to limit warming to the Paris Agreement temperature target of 1.5 °C by mid-century.[136] Instead, fast mitigation of non-CO_2 GHG emissions should go hand-in-hand with decarbonization to slow the rate of warming to under 0.3 °C per decade.[137] The IPCC AR6 concluded that early reductions in CO_2 and further reductions in non-CO_2 emissions, like N_2O, are essential to meet the Paris temperature goal.[138]

Mitigation measures for the industrial sector industry comprise thermal and catalytic decomposition technologies with efficiencies from 85 to 96%.

Abatement technology for industrial N_2O emissions has been available and utilized by manufacturers in developed countries since the 1990s.[139] In fact, the use of abatement technology in some adipic acid, nitric acid, and caprolactam plants caused production-related N_2O emissions to decrease between 1990 and 2010 despite increases in the overall production of these acids.[140]

The abatement and mitigation potentials for select N_2O emissions reduction technology are summarized in Table 2 below.

Gradually installing single and dual abatement technology in all adipic acid manufacturing plants could reduce N_2O emissions by 90% by 2035 and 94% by 2050.[141] In developed countries, deploying cost-effective abatement technology in nitric acid plants can reduce these plants' N_2O emissions by up to 63%. Opportunities exist in developing countries as well.[142]

Table 2. Industrial N_2O Emissions Reduction Technology and Mitigation Potentials by 2030

Technology	Description	Technical Efficiency	Mitigation Potential ($MtCO_2e$/yr)
Adipic Acid Manufacturing			
Thermal/catalytic decomposition	Gaseous N_2O is directed to a reductive furnace for combustion. N_2O is converted to N, producing NO and some residual N_2O as by-products. This option is applicable to adipic acid manufacturing plants that do not currently operate with abatement technology.	96%	~ 4.2
Nitric Acid Manufacturing			
Non-selective catalytic reduction	Similar to thermal destruction but with the aid of reagent fuel (natural gas, propane, butane, or hydrogen) instead of combustion. Typically costs more than other methods.	95%	~ 0.87
Direct catalytic decomposition	Similar to thermal destruction but with the aid of catalysts; destruction chamber located after the absorption tower to catch tail gas. This option is typically available for most existing nitric acid production plants, but effectiveness depends on site-specific factors.	95%	~ 0.87
Catalytic decomposition in the burner	Similar to thermal destruction but with the aid of catalysts. Best applied to old nitric acid production plants, retrofitting required.	85%	~ 0.78

Source: Technical efficiency measures the effectiveness of the selected abatement measures in converting N_2O into nitrogen and water. *See* U.S. EPA (2019) Global Non-CO_2 Greenhouse Gas Emissions Projections & Marginal Abatement Analysis at 5-33–5-36.

Catalytic or thermal reduction is the most effective method to reduce N_2O emissions, achieving up to 99% efficiency, although 90–95% is more typically observed.[143]

The U.S. EPA estimates China can achieve 61% of its national abatement potential at breakeven prices below US$ 10 per ton of CO_2e (tCO_2e). Similarly, the U.S. can reach 49% of its national abatement potential at breakeven prices below US$ 10/tCO_2e.[144]

Mitigation measures for the agriculture sector have lower emissions reductions but are an essential piece of the N_2O puzzle.

The top ten N_2O-emitting countries are responsible for approximately 60% of direct soil N_2O emissions globally. These countries can reduce their N_2O emissions by approximately 68% through cropland mitigation measures.[145] Globally, about 30% of direct N_2O emissions from croplands can be mitigated without reducing yields.[146]

The countries with the largest potential for reducing agricultural N_2O emissions are China, the U.S., India, Brazil, and Mexico.[147] Farming systems in northern and southern Europe also have significant potential to increase their nitrogen use efficiency[148]—the amount of nitrogen reaching the product as a percentage of the nitrogen input.[149]

Note that the effectiveness of improving fertilizer use to reduce N_2O emissions depends on context. Sub-Saharan Africa has one of the lowest fertilizer consumption rates, and these countries need to increase their fertilizer use to meet future food needs.[150]

Table 3. Emissions Mitigation Potential of Agricultural Technology or Practices

Mitigation Technology	% Reduction	Mitigation Practice	% Reduction
Biochar amendment	−26.6	Organic fertilizers	+4.8
Optimization of fertilizer rate	−31.2	Diversified crop rotation	+8.6
Slow- or controlled-release fertilizer rate	−33.0	Deep fertilization	+18.6
Nitrification inhibitors	−44.1	No-tillage	+11.7
Urease inhibitors	−22.5	Reduced tillage	+3.7
Combined inhibitors	−49.4		
Drip irrigation	−26.5		

(+) indicates an increase in emissions.
Source: Grados D., Butterbach-Bahl K., van Groenigen K. J., Olesen J. E., van Groenigen J. W., & Abalos D. (2022) Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems, Envtl. Research Letters 17:114024, 6.

As Table 3 demonstrates, some agricultural interventions are more effective in reducing N_2O emissions than others. Gao, *et al.* (2023) found that increasing global nitrogen use efficiency from the current 42% to 67% by 2050 can reduce nitrogen demand by 48% by 2050.[151] This improved efficiency can be achieved through measures like proper irrigation, planting crops that use fertilizers more efficiently, and applying the correct fertilizers at the right rate, time, and place.[152] Other interventions like the use of nitrogen inhibitors and biochar amendment also reduce N_2O emissions considerably.[153]

Using organic fertilizer, diversifying crop rotations, reducing or avoiding tillage, and using cover crops could increase N_2O emissions, even as these interventions result in a wide range of other benefits.[154] Understanding soil and climate conditions in agricultural systems will be vital in choosing the most effective mitigation measures.

Biochar reduces N_2O emissions and sequesters carbon.

Biochar is a solid material obtained from burning biomass, such as wood, manure, and crop residues, in a closed container.[155] Applying biochar to paddy rice has been shown to reduce N_2O emissions by an average of 20–40%.[156]

Potential co-benefits of using biochar include increased crop yield, the adsorption of organic pollutants, and reduction of methane emissions. Biochar also effectively sequesters carbon; it can retain about 50% of the carbon in feedstock after processing, and it resides in the soil for more than 100 years after application.[157]

Understanding soil conditions is necessary to maximize the benefits from biochar application. Lin, *et al.* (2024) found that biochar is particularly effective in mitigating N_2O emissions in acidic and alkaline soils but is less effective in pH-neutral soils.[158]

Between 2020 and 2050, the greatest potential benefits for biochar application are in Asia and the Developing Pacific at 793 $MtCO_2$/yr in reduced N_2O emissions with a cost of up to US$ 100/tCO_2 per year. For developed countries, biochar application with the same costs can reduce N_2O emissions by 447 $MtCO_2$/yr.[159]

Seed dressings and soil additives reduce N_2O emissions, with some proprietary technologies offering greater reductions in specific applications.

As shown in Table 3 above, N inhibitors can reduce N_2O emissions by about 44%.[160] Other studies have found that N inhibitors can reduce emissions by 34–38% at a cost of ~US$ 0.10–0.22/kg N, with marginal costs of ~US$ 58–115/tCO_2e.[161]

SOP (Save Our Planet)[162] offers a product line that provides another solution for reducing agricultural N_2O emissions. "SOP LAGOON" is a commercial manure additive and a GHG inhibitor. Studies show that treating cattle manure with SOP LAGOON reduces N_2O emissions by 45–100%.[163]

SOP COCUS MAIZE+ (SCM) is a gypsum seed dressing that improves maize nutrient uptake by increasing root system development and establishment, effectively reducing the need for fertilizers.[164] A peer-reviewed study showed that using SOP seed dressing on maize sustained yields despite a 30% decrease in applied nitrogen fertilizer.[165] This resulted in a 23% decrease in N_2O emissions.[166]

Alternative farming practices comprise several techniques that can reduce N_2O emissions.

Precision agriculture is a mixture of different agricultural practices and technologies, including variable rate technology (VRT), that allows farmers to apply the optimum amount of fertilizer to each crop through sensor technology and instrumentation.[167] VRT prevents over-fertilization of fields.[168] Studies have found that the use of VRT can increase yield by 1–10% while saving from 4 to 37% of nitrogen fertilization.[169] VRT can reduce N_2O emissions by 19–24% at a cost of ~US$ 0.05–0.11/kg N applied, with marginal costs of ~US$ 6–111/tCO_2e.[170]

Another strategy is to use plants that are efficient in fixing nitrogen from the air. For example, clover, a nitrogen-fixing plant, when used in pastures can reduce fertilizer requirements by up to 100 kg N per hectare and N_2O emissions by 40% while increasing farm profits.[171]

No-till farming is the practice of leaving the soil untilled with the organic residue left on the soil surface. This minimizes the breakdown of soil organic matter and reduces the resulting N_2O emissions.[172] A 2021 study found that practicing no-till farming can result in a yearly mean N_2O reduction of 549 kg CO_2e/hectare.[173] However, soil type is an important factor in determining the impact of no-till farming; some soil structures produce anoxic (very low or no oxygen) conditions that can lead to N_2O emissions rather than reductions.[174] As Table 3 shows, no-till farming could increase N_2O emissions and should be studied before adoption.

Manure management can reduce N_2O emissions and offers secondary benefits of lower methane and NH_3 emissions.

Some livestock manure management strategies present opportunities to mitigate agricultural N_2O, methane, and NH_3 emissions.[175] Manipulating the diet of livestock animals to optimize nitrogen levels and increase dry matter results in lower N content and less methane emissions from manure.[176] Providing cattle and swine feed with higher digestibility reduces enteric fermentation and manure production.[177]

Biochar reduces soil N_2O emissions by inhibiting nitrification. Increasing soil aeration and bulk density can also decrease methane emissions in manure-affected soils.[178] Silvopastoral systems—farming systems that introduce trees and shrubs in pastures—can decrease N_2O and methane emissions by improving soil cover and health, improving livestock diets, and introducing dung beetles that limit the interaction of manure with microorganisms in the soil.[179]

VI. Barriers to implementing N_2O abatement strategies can be overcome.

Adoption of N_2O mitigation technology is slow despite the known benefits and the availability of cost-effective solutions. Major barriers prevent adoption, including:

- Uncertainties in measurement
- A lack of adequate policies to incentivize and support the adoption of mitigation technology
- Risk-averseness of manufacturers and farmers

These barriers can be overcome through funding, policy, and information-sharing.

Improved measurement techniques can make it easier to quantify N_2O emissions reductions for different abatement options.

N_2O emissions, especially agricultural emissions, can be difficult to measure because they vary based on environmental conditions.[180] However, cost-effective measurement methods like emission factors are improving.[181] Contrary to the assumptions in the IPCC National GHG Inventory Guidelines,[182] Kanter, *et al*. (2020) found that N_2O emissions reductions from fertilizer overapplication are non-linear, meaning that the initial amount of fertilizer applied greatly influences the impact of decreasing fertilizer application.[183] Thus, even moderate decreases in "highly fertilized" regions can result in significant N_2O emissions reductions.[184]

Researchers based at the University of Minnesota developed a knowledge-guided machine learning model for agroecosystems (KGML-ag) that allows for more accurate measurement of agricultural N_2O emissions. KGML-ag "pre-trains" inputs and outputs that were generated by an advanced process-based model instead of merely relying on machine learning to map patterns. It outperformed both pure machine learning and process-based models in predicting N_2O emissions.[185] Additionally, KGML-ag predicted the behavior of other variables like ammonia and CO_2.[186] These promising new developments may close the gaps in understanding and measuring agricultural N_2O emissions and other pollutants, and GHG emissions from the agriculture sector.

Policies and legislation can encourage the adoption of N_2O mitigation solutions.

Institutional support through policy and legislation is vital in N_2O mitigation. For example, China participated in the Kyoto Protocol's Clean Development Mechanism in 2007 and received technical and financial support to install thermal and catalytic decomposition in their nitric acid, adipic acid, and caprolactam manufacturing plants.[187] However, this support was insufficient to ensure the continued operation of abatement technology,[188], and it was insufficient to cover all manufacturing plants in China. [189] To date, China does not regulate industrial N_2O emissions.[190] Additional policy guidelines and support will encourage faster emissions reductions.[191]

In agriculture, farmer welfare and rural livelihood subsidy programs may pose challenges to implementing regulations focused on GHG reduction.[192] Some countries continue to use fertilizer subsidies, even though subsidies contribute less and less to farm productivity.[193] In some instances, subsidies create incentives for excessive fertilizer application. This contributes to GHG emissions, discourages product innovation, and crowds out agricultural research and development investments. [194] However, these programs can also introduce incentives for N_2O mitigation, especially in developing countries where the adoption of new technology or practices depends significantly on access to subsidy programs.[195]

In the U.S., suppliers, government entities, and farming associations have vehemently opposed Federal or state regulation of nitrogen fertilizer application. However, these entities may be open to policies that create market-based incentives to reduce N_2O emissions or reward voluntary action. For example, the American Farming Bureau has opposed the implementation of non-voluntary commercial fertilizer management plans to address natural resource concerns, [196] but the organization states support for "incentives to industries seeking to become more energy efficient or to reduce emissions of identifiable atmospheric pollution and the means of preventing it."[197] The Florida Farm Bureau has stated it will support voluntary measures in environmental regulations on farms.[198] Note that some state governments have been slow to provide resources to enforce new fertilization standards.[199]

Agricultural incentives should benefit the environment and, to the extent possible, not have a negative impact on agricultural yields. These incentives should also include education and training for farmers as well as logistical support.[200] Targeted extension services can increase the adoption rate of new, climate-friendly technology.[201]

Information-sharing can alleviate skepticism and risk aversion regarding new technologies in the agriculture sector.

Attitudes toward the adoption of new technology depend on farmers' financial security, education, the quality of information they receive on these technologies,[202] whether the sources of information are trusted, and farmers' ages.[203] The perceived utility of new technology is a particularly important factor in decision-making.[204] Farmers can be reluctant to adopt technology and practices that deviate significantly from existing practices[205] when the benefits are too variable.[206]

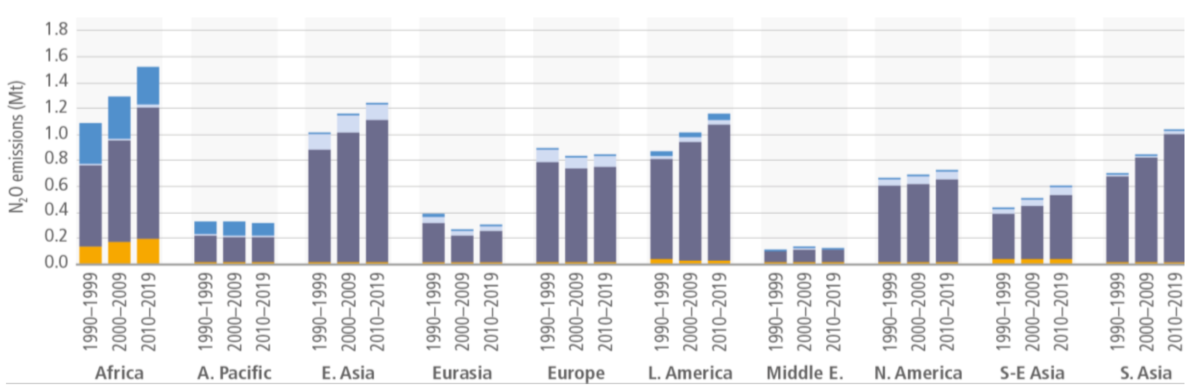
Demonstration projects can be helpful in encouraging adoption of new technology and practices.[207] In New Zealand, a study found that farmers who participate in networks for discussing finances or environmental performance are more likely to adopt new technology.[208] In China, farmers rely on personal experience over research and agronomic advice when they perceive that the suggested fertilization rate is too conservative or underestimates crop response.[209]

Finally, it should be noted that climatic conditions and fertilizer use vary from region to region; there's no one-size-fits-all policy that works for all situations. Asia and the Developing Pacific have the highest fertilizer use. Between 2020 and 2050, these two regions offer the greatest mitigation potential—161.8 $MtCO_2e/yr$ for Asia and 37.1 $MtCO_2e/yr$ for the Developing Pacific.[210] On the other hand, Sub-Saharan Africa has the lowest fertilizer consumption rates and requires increased fertilizer use to meet future food needs.[211]

VII. Countries should strengthen N_2O policies, programs, and legislative models.

All regions have shown increased agricultural N_2O emissions since 1990, with Africa, Southern Asia, and Eastern Asia having the largest growth.[212] Emissions from Europe and Eurasia declined briefly due to environmental regulations in the 1980s but have been increasing since 2010.[213] Decreases in N_2O emissions from Europe and other countries in the West are offset by increases in other regions.[214]

Figure 3. Estimated average Agriculture, Forestry, and Other Land Uses (AFOLU) N_2O emissions for three decades according to Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) data by ten global regions



FOLU in orange, agriculture categories all other colors. Nabuurs G., et al. (2022) Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU), in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7–27 (see Figure 7.8).

As detailed in Appendix A, countries vary in how they control N_2O emissions. The European Union (EU) includes N_2O in its emissions trading system and imposes a broad range of pollution regulations that can benefit N_2O mitigation. The U.S. has invested in research and development of sustainable fertilizers and farming practices through the Global Fertilizer Challenge. China, Canada, New Zealand, and private companies have voluntary programs encouraging efficient fertilizer use by promoting available technology through education or offset credits. The Netherlands recently launched a program targeting nitrogen GHG emissions from the agriculture sector. These domestic efforts should be studied and scaled up, and the resulting experience shared with N_2O hotspot countries.

High-integrity carbon markets can be designed to provide financing for mitigation activities and complement regulatory policies.

The U.S. White House released a set of principles for responsible participation in voluntary carbon markets.[215] The Climate Action Reserve, a U.S.-based nonprofit, adopted a China adipic acid production protocol (for carbon-credit purposes) in 2023 and a U.S. adipic acid production protocol in 2020. These protocols create incentives for installing and operating N_2O abatement technology in adipic acid manufacturing plants in China and the U.S. The Climate Action Reserve has also developed a U.S. nitric acid production protocol.[216]

The Clean Development Mechanism of the Kyoto Protocol has provided lessons learned regarding safeguards to incorporate in protocols.[217] To prevent "carbon leakage"—when companies change locations to a country with less stringent GHG controls—the Climate Action Reserve China Adipic Acid Production Protocol sets a minimum baseline abatement efficiency of 90% and gives credits only for emissions reduction above this baseline.[218] Plants that already have abatement technology with efficiency higher than 90% are subject to higher baselines. In addition, adipic acid manufacturers cannot increase production beyond their maximum production capacity as reported in the latest government filings (e.g., environmental impact assessment reports and performance check reports) to claim additional credits for N_2O abated.[219] Manufacturers who intend to increase production by more than 10% of their maximum production capacity must prove that the increased production is a response to increasing market demand.[220] Requirements like these are consistent with high-integrity carbon markets and could be part of a phase-in of regulations requiring facilities to abate a minimum of 90% of their N_2O emissions.

Locus Agricultural Solutions (Locus Ag) is a private company that develops agricultural technology to increase carbon sequestration and reduce GHG emissions. Locus Ag has also launched its own program called CarbonNOW.[221] The CarbonNOW program allows U.S. farmers to generate carbon credits by adopting sustainable production practices. Participating farmers are guided through measuring, verifying, and marketing carbon captured in their soils.[222] Locus Ag offers a suite of products promoting sustainable crops, including Rhizolizer Duo, a microbial soil amendment encouraging root growth and increasing crop nutrient uptake.[223] Locus Ag claims that Rhizolizer Duo decreases N_2O emissions by 75–85% in corn, 87% in citrus plants, and 60% in potatoes.[224]

VIII. The Montreal Protocol is the best mechanism to control global N_2O emissions.

N_2O is both an ODS and a climate pollutant that should be included in the Montreal Protocol, starting with controlling emissions from the industrial sector. Note that there is already precedent for adding new substances to the Montreal Protocol. In 2016, the Kigali Amendment brought the production of HFCs—high-GWP substances that do not deplete the ozone layer—under the Montreal Protocol's jurisdiction and mandated the HFC phasedown.[225] Article 2(10) of the Protocol allows Parties to add N_2O and other substances to the list of controlled substances by amendment and to determine the mechanism, scope, and timing of control measures,[226] based on procedures that the Parties set forth, including assessments by the Protocol's expert assessment panels.[227]

According to the 2022 Quadrennial Assessment of Ozone Depletion, the increase in total N_2O emissions has accelerated over the past 20 years and now exceeds the highest atmospheric projections.[228] As mentioned previously, natural N_2O emissions have remained stable, making anthropogenic N_2O emissions the only possible cause. In fact, 2020 anthropogenic N_2O emissions exceed the ozone-depleting potential of peak 1987 chlorofluorocarbon (CFC) emissions by 20%.[229] As also stated in the Quadrennial Assessment, reducing N_2O emissions by an average of 3% in the next 50 years can result in ozone recovery equal to 25% of the impact of eliminating all other ODS emissions beginning in 2023.[230] Full recovery of the ozone layer will be delayed if N_2O emissions continue to increase.[231]

This reduction in N_2O emissions would also reduce radiative forcing—the change in the balance of solar radiation entering the atmosphere and infrared radiation exiting as heat—by 0.04 W m^{-2} averaged over 2023–2100. This is more than half the decrease in radiative forcing that comes from eliminating all HFCs.[232]

As discussed in Section V, agricultural and industrial processes emit N_2O as a by-product. As an initial step, Parties to the Montreal Protocol could request the Assessment Panels to produce a report on the ozone impacts of N_2O and any existing, cost-effective solutions for its mitigation. Industrial N_2O emissions are point-source emissions that could be controlled similarly to HFC-23 under the Kigali Amendment, *i.e.*, by requiring their destruction through the installation of approved abatement technology. Developing country Parties that host acid production plants should be enabled through capacity-building and information-sharing, with their efforts supported through the Protocol's Multilateral Fund.

On the other hand, agricultural N_2O emissions are non-point-source emissions. Parties could learn from their experience controlling methyl bromide (MeBr), an agricultural fumigant injected into soils to control pests. Parties to the Montreal Protocol are phasing out MeBr through the substitution of tested alternatives, even though infrastructure and supply chains for MeBr are already established.[233] N_2O emissions from agriculture could be addressed similarly. After the most suitable and cost-effective solutions are identified, demonstration projects can encourage acceptance. While Parties will need a flexibility mechanism in place, N_2O-emitting activities should only be allowed after all economically feasible steps to minimize emissions are taken.

IX. Policies that continue research and support for agricultural N_2O mitigation options are required.

N_2O is the third most important GHG and currently the most significant ODS. Despite the availability of cost-effective mitigation measures in key sectors, N_2O emissions remain largely uncontrolled and continue to increase. Below are some additional policy recommendations to consider in advancing action on N_2O.

Integrated nitrogen management needs to be supported.

Agricultural N_2O emissions are a by-product of excess nitrogen that undergoes transformation through the nitrogen cycle. As discussed in Sections II and V, this excess nitrogen also results in other forms of nitrogen pollution. Measures that mitigate N_2O emissions and nitrogen pollutants should be studied, scaled up, and supported.

Existing bodies like the UNEP Nitrogen Working Group should be enabled and supported to provide expertise and technical assistance to developing countries that wish to create National Action Plans. Creating national nitrogen action plans could aid in identifying nitrogen pollution sources and solutions.[234] See Appendix B for information on the UN Sustainable Nitrogen Management Resolution and the Colombo Declaration

More research is needed for agricultural N_2O mitigation solutions that enhance food security and support farmers' livelihoods.

Policies that account for the environmental impacts of the agriculture sector have been difficult to implement due to reasons discussed in Section V. Further research is needed to understand the impacts and benefits of N_2O mitigation on food security and farmer livelihoods.

In Europe, the Convention on Long-Range Transboundary Air Pollution (LRTAP) Task Force on Reactive Nitrogen has researched the synergies between nitrogen management, food, environment, and health. Similar efforts should be conducted in other regions, particularly Asia, where N_2O emissions and nitrogen pollution are high, and in Sub-Saharan Africa, where food security remains a significant issue.

See Appendix B for information on multilateral organizations focusing on food security.

X. Other international agreements present opportunities to mitigate N_2O emissions.

Climate protection provisions within the Paris Agreement may be able to reduce N_2O emissions since N_2O is a known climate pollutant. The Convention on Long-Range Transboundary Air Pollution does not cover N_2O, but ammonia (NH_3) emissions are included—and NH_3 oxidation creates reactive nitrogen species, including N_2O.

The Paris Agreement

The Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC) aims to limit global temperature increase to well below 2 °C above pre-industrial levels. Each country creates climate action plans—Nationally Determined Contributions (NDCs)—for reducing GHG emissions.[235] More than 90% of submitted NDCs include N_2O emissions in their list of covered gases.[236] One Party, Uruguay, included explicit N_2O mitigation targets below 1990 levels,[237] setting an economy-wide target of reducing N_2O emissions by 51–57% and a livestock-sector target of 37–43%.[238] Mexico included its participation in the Nitric Acid Climate Action Group (NACAG) as its contribution to N_2O emissions reduction.[239]

Prior to the Paris Agreement, Parties received support to adopt industrial N_2O abatement technology through the Clean Development Mechanism.[240] The Kyoto Protocol expired in 2020,[241] and as a result, some countries did not keep their abatement technology in operation without the continued financial support.

Countries with industries participating in abatement projects utilizing the carbon market mechanisms of Paris Agreement Article 6 should be required to enact national legislation ensuring the permanent operation of abatement technology. Otherwise, adipic and nitric acid manufacturers may become dependent on international funding to continue reducing their N_2O emissions.[242]

The Convention on Long-Range Transboundary Air Pollution

N_2O is not among the gases covered by the Convention on Long-Range Transboundary Air Pollution (LRTAP), a regional agreement of Europe, North America, Russia, and Eastern Bloc countries. However, LRTAP's Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-Level Ozone (Gothenburg Protocol) sets national emission ceilings for ammonia (NH_3)[243] and requires Parties to apply ammonia control measures.[244] These measures include limiting ammonia emissions from urea fertilizer applications,[245] prohibiting ammonium carbonate fertilizers,[246] using low-emission slurry techniques,[247] and using low-emission slurry storage systems or techniques for large pig and poultry farms.[248] To the extent appropriate, best available techniques should be implemented to prevent and reduce ammonia emissions.[249]

To aid Parties in complying with their obligations, the LRTAP Task Force on Reactive Nitrogen (TFRN) in 2020 produced a guidance document addressing nitrogen emissions.[250] The *Guidance Document on Integrated Sustainable Management* is non-binding but aims "to foster change by clearly identifying the multiple co-benefits of reducing nitrogen emissions, as relevant for air quality, climate change, water quality, human health, ecosystems and economy."[251] The *Guidance Document* explains the linkages between N pollution and climate, including the role of N_2O in driving climate change. It also contains information on abatement measures that reduce nitrogen losses, such as the precise application of fertilizers[252] and the use of N inhibitors.[253]

In 2022, the TFRN published *Nitrogen Opportunities for Agriculture, Food & Environment: UNECE Guidance Document on Integrated Sustainable Nitrogen Management*. This report outlines principles and measures to reduce nitrogen pollution from food systems.[254] It aims to strengthen the development of strategies to address pollution and establish coherent "packages of measures" to maximize synergies.[255] In 2023, TFRN published the second European Nitrogen Assessment Special Report on Nitrogen & Food titled *Appetite for Change: Food System Options for Nitrogen, Environment & Health*. The report discusses the state and impact of the current levels of nitrogen use efficiency in Europe as well as options for improvement, including optimizing fertilizer management in farms.

XI. Conclusion

The Montreal Protocol is the best mechanism to control N_2O emissions. Similar to the strategy that brought HFC-23 and MeBr under the Protocol, Parties can begin to control N_2O by adopting abatement measures for industrial emissions. As discussed in Section VI, cost-effective measures to abate industrial N_2O emissions are already available. With adequate support and legislation, Parties that host adipic acid, nitric acid, and caprolactam plants could require installation of abatement technology and ensure its continued operation throughout the lifetime of the plants.

Appendix A: Survey of national/regional N_2O strategies with policy recommendations

European Union

In 2018, the EU outlined its strategy to reduce GHG emissions to net zero by 2050, setting a target of reducing its agricultural N_2O and methane emissions by approximately 62% (from 461 $MtCO_2e$ to 286 $MtCO_2e$) by 2050.[256] In May 2020, the EU published its Farm to Fork Strategy that sets targets of decreasing soil nutrient loss by 50%, lowering fertilizer use by 20%,[257] and increasing the share of agricultural land to at least 25%—all by 2030.[258] Decreasing fertilizer use could reduce N_2O emissions as crops leave less nitrogen unused.

In line with its climate ambitions and its Methane Strategy, the EU should consider adopting combinations of N_2O and methane emissions reduction measures to maximize reductions in its agricultural sector. One study has shown that combined mitigation measures targeting the largest emission flows, like feed additives, can potentially reduce N_2O and methane emissions by 54%.[259]

The EU's policies and legislation to control nitrogen pollution also contribute to N_2O mitigation. The Urban Waste Water Treatment Directive (EEC, 1991) aims to reduce nitrogen in waste streams by up to 75%, which reduces the amount of N_2O released to the atmosphere by wastewater.[260]

The Sludge Directive (86/278/EEC, 1986) regulates the use of sewage sludge in agriculture.[261] This Directive requires Member States to consider the plants' nutrient requirements and to avoid impairing soil and groundwater quality.[262] It also sets rules on using sewage sludge as fertilizer and requires Member States to assess nitrogen content in sludge to determine whether treatment is necessary before application.[263]

The EU Nitrates Directive of 1991—aimed at protecting water quality—restricted the quantity of manure nitrogen applied on farm fields per hectare.[264] The Directive demands that Parties designate as vulnerable zones all areas of land within their borders that drain into waters susceptible to pollution and establish action plans to protect these waters.[265] The prescribed protective measures include limiting or even prohibiting fertilizer and manure use on agricultural fields.[266] Member States are required to report on the nitrate concentrations in groundwaters and surface waters every four years.

The EU Emissions Trading System (ETS) covers N_2O emissions from nitric and adipic acid production.[267] Nitric and adipic acid manufacturers obtain allowances based on GHG performance benchmarks and according to EU-wide allocation rules.[268]

The EU's Carbon Border Adjustment Mechanism (CBAM)[269] requires importers of nitric acid to register with national authorities and purchase CBAM certificates at prices based on weekly ETS allowances.[270] Importers must declare the emissions embedded in their imports and surrender the corresponding number of certificates annually.[271] Importers can deduct any carbon price already paid by producers.[272] CBAM will be fully implemented after 1 January 2026. It is expected to capture more than 50% of the ETS-covered emissions.[273]. During the transitional phase (1 October

2023 to 1 January 2026), importers must report emissions but will not be required to make financial payments or adjustments.[274]

Netherlands

The Netherlands has the second-highest nitrogen surplus in Europe—over double the average regional numbers from 2010–2015[275]—with 118 of 162 nature reserves at risk of severe nitrogen pollution.[276] The European Court of Justice and the Netherlands Council of State have ruled separately that the Dutch permitting policy for nitrogen polluters was contrary to EU regulations.[277]

On 10 June 2022, Christianne van der Wal, Dutch Minister for Nitrogen and Nature Policy, presented a plan to achieve reductions in domestic nitrogen GHG emissions.[278] The Dutch government aims to reduce nitrogen GHG emissions by 40% before 2030 by setting area-specific emission reduction objectives at the provincial level.[279] Dutch farmers opposed the regulation, arguing that the policy would economically burden farmers and force them to shrink or close their operations.[280] To quell the unrest, the Dutch government allotted approximately US$ 25.6 billion to buy out up to 3,000 of the largest emitting farms.[281]

United States

At the July 2024 White House Super Pollutants Summit, two U.S. companies announced new actions on industrial N_2O emissions that could reduce emissions by over 50% from 2020 numbers by 2025.[282] Ascend Performance Materials, the largest adipic acid producer in the U.S., announced that it is in the process of eliminating virtually all its N_2O emissions at its facility in Florida by installing additional abatement technology.[283] ClimeCo, the largest developer of N_2O abatement projects in the U.S., announced that new projects will come online by early 2025 to reduce N_2O emissions at three facilities by about 95%.[284] ClimeCo also announced that it will launch four new adipic acid projects in China that could prevent N_2O emissions equivalent to 60 million tons of CO_2.[285]

In 2021, the U.S. launched the Global Fertilizer Challenge, recognizing that "[c]limate-driven food security shocks will continue to cause food scarcity and suffering if steps are not taken to increase food system resilience."[286] Reducing global fertilizer loss and waste by just 10% would save more than enough fertilizer to create stable agricultural production in Africa.[287] Additionally, increasing fertilizer use efficiency can reduce natural gas dependence because nitrogen fertilizer production consumes up to 4% of the global natural gas supply.[288]

The Global Fertilizer Challenge raised US$ 135 million in new funding to support research, demonstration, and training in countries with excessive fertilizer usage and loss. The Challenge also encourages the adoption of efficient nutrient management and alternative solutions.[289] It funds several projects, including the Efficient Fertilizer Consortium. This public-private partnership finances applied research into fertilizers that increase nutrient-use efficiency and reduce nitrogen losses to the environment. The Global Fertilizer Challenge also finances bilateral research and development projects like Fertilize 4 Life, a scientific collaboration between Brazil and the U.S. Fertilize 4 Life is among the programs supported by Fertilize Right, which aims to promote the 4Rs of nutrient management (right source, right rate, right time, right place) in agriculture systems in Brazil, Colombia, Pakistan, and Vietnam.

The U.S. also established a US$ 500 million program to support sustainable fertilizer production and to strengthen support for precision agriculture and other techniques to improve nitrogen use efficiency.[290]

Pursuant to Executive Order 13990, U.S. President Joe Biden re-established the Inter-Agency Working Group (IWG) to update the estimates of the social costs of N_2O, CO_2, and methane.[291] The IWG calculated the social cost of N_2O at US$ 18,000 per metric ton in 2020 and US$ 33,000 per metric ton in 2050.[292] These estimates have been used in the U.S. EPA's analyses for rulemaking.[293]

China

According to official data from the Chinese government, China's N_2O emissions were 0.52 $GtCO_2e$ (1.9 Mt N_2O) in 2018. The agricultural sector contributed the most emissions (49.2%), followed by industrial processes (23%).[294] Consistent with this reporting, Tian, *et al.* (2024) estimated that China's N_2O emissions in 2020 were ~0.59 $GtCO_2e$ (2.2 Mt N_2O), with 48% the preceding decade's emissions attributed to agriculture.[295]

Agricultural emissions in China began slowing in 2016 as a result of policies such as the Zero Growth in Fertilizer Use Plan,[296] that aimed to optimize the use of nitrogen fertilizers.[297] In 2020, the program decreased fertilizer application by about 11% from 2015 levels while increasing yield by about 8%.[298] In 2022, China issued the "Implementation Plan for Emission Reduction and Carbon Sequestration in Agriculture Sector and Rural Area."[299] The Plan further promotes reducing N_2O emissions by improving nitrogen fertilizer use efficiency in farmland and improving livestock and poultry manure resource reutilization. China aims to increase the efficiency of chemical fertilizers and pesticides from 40% in 2020[300] to 43% by 2025.[301] China also set a target for increasing comprehensive reutilization of livestock and poultry manure from 78% in 2023[302] to over 80% nationwide by 2025,[303] and over 85% by 2030.[304] Last but not least, China is looking into low-carbon compensation mechanisms to create incentives for N_2O mitigation action in the agricultural sector.[305]

Roughly 63% of China's cropland N_2O emissions could be reduced by 2050 through agronomy practices.[306] Reducing nitrogen fertilizer rates, applying high-efficiency fertilizers, and optimizing irrigation present the largest potential for reducing N_2O emissions in agricultural areas growing fruits and vegetables.[307] For other crops like maize, relocating sowing areas to regions with lower emission factors could also mitigate N_2O emissions.[308] Climate policies with direct quantitative nitrogen reduction targets and improved farmer education could encourage adoption of these mitigation measures.

Unlike the progress being made in China's agricultural sector, N_2O emissions from industry and energy have increased rapidly since 2005 and are the fastest-growing source of national emissions.[309] China is the largest source of N_2O emissions from adipic acid manufacturing, with 11 plants responsible for about 93% of global sectoral emissions.[310] Estimates show that the social benefits from co-mitigation of climate change and nitrogen pollution via reduced N_2O emissions significantly outweigh the implementation costs. In scenarios with the strongest mitigation, US$ 1.964 trillion in societal gains (climate, health, and ecosystem benefits) can be achieved in

2050 at the cost of US$ 240 billion per year.[311] The U.S. EPA (2019) estimates that China can achieve 61% of its industrial N_2O abatement potential at breakeven prices below US$10/t$CO_2$e.[312]

This presents an important climate mitigation opportunity within the context of both China's domestic policy development and international engagement with China. For domestic policy considerations, China incorporated a commitment to "study and formulate nitrous oxide reduction plans for key industries" in its Nationally Determined Contribution 2022.[313] In December 2023, China released a policy document that indicated interest in researching the development of non-CO_2 GHG emission-control action plans.[314] In September 2024, China convened a workshop on controlling N_2O emissions.[315] On bilateral/multilateral engagement with China, it is noteworthy that the U.S. and China indicated they "intend to cooperate on respective measures to manage N_2O emissions" in the Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis.[316] At the White House Super Pollutants Summit in 2024, U.S. industry announced action to reduce industrial N_2O emissions by over 50% by 2025.[317] China's revived voluntary GHG emission trading mechanism may be deployed to help finance the installation of industrial N_2O abatement technologies.[318]

New Zealand

New Zealand is in the second year of its five-year *He Waka Eke Noa* (Primary Sector Climate Action Partnership) Programme. The program is a state-initiated and monitored collaboration between farmers and industry to encourage climate action through farm planning and emissions pricing.[319] New Zealand aims to finalize the program by 2025 and implement its emissions trading system by 2025.

New Zealand has proposed taxing agricultural GHG emissions like methane and N_2O.[320] The proposed levy will apply to farmers who meet the threshold for herd size and fertilizer use and will be set every 1–3 years based on the advice of farmers and the Climate Change Commission.[321] All revenue will go toward research and development, with incentive payments made to farmers who adopt climate-friendly practices.[322] Farmers protested the proposal, which underwent public consultation in October 2022, claiming that it would harm livelihoods and raise food prices.[323] As a concession, the New Zealand government pushed back the start date for the tax on farm emissions from the beginning to the end of 2025 to give farmers more time to adjust to the tax policy.[324]

Canada

On 5 March 2021, the Canadian government proposed regulations to establish a federal carbon offset system composed of several offset protocols that allow participants, including farmers, to generate carbon offset credits tradable to industrial GHG emitters.[325] In May 2024, Canada published the protocol on improved forest management on private land.[326] Canada is also considering protocols for avoiding the conversion of grasslands and reducing nitrogen oxide emissions from agriculture fertilizer, and livestock manure management.[327]

Canada's strengthened climate plan includes a voluntary fertilizer reduction target of 30% below 2020 levels by 2030.[328] The new Sustainable Canadian Agriculture Partnership (Sustainable CAP) provides CAD 3.5 billion in financing to support activities in the federal, provincial, and territorial agriculture and agri-food sectors,[329] including reductions of agricultural GHG emissions by "three to five megatonnes" from 2023–2028.[330] Canada's fertilizer policy highlights the 4R Nutrient

Stewardship approach developed by Fertilizer Canada.[331] The 4R focuses on implementing best practices tailored to the conditions of each farm. Certified crop advisors develop management plans for sustainable fertilizer application. Data from the Canadian government shows that implementation of the 4R program can reduce fertilizer-related emissions without yield penalties.

Appendix B: Multilateral initiatives addressing N_2O emissions

The Climate and Clean Air Coalition

The Climate and Clean Air Coalition (CCAC) is a voluntary partnership of governments, international organizations, businesses, and scientific institutions committed to mitigating air pollution and climate change through actions to reduce climate super pollutants.[332] At the 28th Conference of the Parties (COP 28) held in the United Arab Emirates in December 2023, CCAC announced that it will conduct an assessment on N_2O to be delivered before COP 29.[333] The N_2O Assessment is expected to be launched in October 2024 at the Meeting of the Parties to the Montreal Protocol, with a soft launch scheduled at the New York Climate Week in September of the same year.[334]

The CCAC works with over 70 countries through project funding and assistance focused on five key areas: (1) national planning and policy development; (2) sector mitigation; (3) science policy; (4) political leadership and cooperation; and (5) climate commitments.[335] The N_2O Assessment could be a first step to more extensive action on N_2O.

The Nitric Acid Climate Action Group Programme

The Nitric Acid Climate Action Group (NACAG) aims to encourage N_2O emissions abatement from nitric acid production plants. NACAG provides guidance and information to governments and plant operators on N_2O abatement technology and regulations.[336] It also provides financial assistance to nitric acid and caprolactam production plants of up to 100% of costs associated with the purchase and installation of abatement technology, provided that the countries in which the plants are located have committed to ensuring that all future nitric acid production installations abate N_2O emissions.[337] The NACAG Programme has 16 partner countries, including Georgia, Tunisia, Zimbabwe, Mexico, Thailand, and Uzbekistan.[338]

The UN Sustainable Nitrogen Management Resolution and the Colombo Declaration

On 15 March 2019, the Fourth Session of the United Nations Environment Assembly (UNEA-4) adopted the Sustainable Nitrogen Management Resolution.[339] Recognizing that anthropogenic reactive nitrogen results in environmental harm and GHG emissions, and realizing that “intersectorally incoherent approaches” in managing the global N cycle is counterproductive, UNEA called on the UNEP to consider establishing an intergovernmental mechanism for coordinating nitrogen polices.[340] Thus, the UNEP Nitrogen Working Group was formed and tasked with exploring options for sustainable nitrogen management.[341] The Working Group held its first briefing session on 8–9 June 2020,[342] in which a Task Team was established to refine the Terms of Reference for the Interconvention Nitrogen Coordination Mechanism (INCOM).[343]

The Working Group is currently discussing options and modalities for improved coordination of policies across the global nitrogen cycle. Among the options being considered are (a) for an existing multilateral agreement, like the Montreal Protocol, to take leadership in global nitrogen governance and (b) for countries to form an intergovernmental coordination mechanism "to make the best possible use of existing networks and platforms to ensure policy coherence and consistency."[344] The Working Group is also supporting countries by identifying action areas in national action plans for the consideration of Member States, organizing expert meetings to allow for technical discussions with nitrogen focal points, and facilitating information-sharing among Member States.[345]

In October 2019, 30 UN Member States, concurrent with the launch of the UN Global Campaign on Sustainable Nitrogen Management, adopted the *Colombo Declaration on Sustainable Nitrogen Management.* Parties to the Declaration agreed to cut N waste by 50% by 2030 as part of their National Nitrogen Action Plans and adopted the *Roadmap for Action on Sustainable Nitrogen Management 2020–2022*.[346] The new global goal spurred the EU to include decreasing nutrient pollution in its Farm to Fork Strategy and the Convention on Biological Diversity to consider adopting a similar target.[347]

At the Fifth Session of the United Nations Environment Assembly (UNEA 5.2), the Assembly adopted Resolution 5/2 on Sustainable Nitrogen Management. The Assembly requested the UNEP Executive Director to identify methods to improve coordination among policies affecting the global nitrogen cycle.[348] Some key concerns that have emerged in discussions include maintaining the independence of Multilateral Environmental Agreements (MEAs),[349] giving the coordination mechanism the capacity to attract, receive, and channel funding toward sustainable N management,[350] and determining the proper timing for MEAs to propose resolutions and decisions authorizing formation and engagement with the mechanism.[351]

Scientific partners in global N governance

The Global Partnership on Nutrient Management (GPNM) is a group of scientists organized under UNEP to respond to the nutrient challenge. Its goal is to "promote effective nutrient management to achieve the twin goals of food security through increased productivity and conservation of natural resources and the environment."[352] In partnership with the Global Environment Facility, the GPNM is implementing the Global Foundations for Reducing Nutrient Enrichment and Oxygen Depletion from Land Based Pollution in support of Global Nutrient Cycle Project.[353]

The International Nitrogen Management System (INMS) is an organization of scientists, industry members, and citizens that aims to build evidence to "support international policy development to improve global nitrogen management."[354] The INMS has four components: (1) tools for understanding and managing the global N cycle; (2) quantification of N flows, threats, and benefits; (3) regional demonstration of a full nitrogen approach; and (4) awareness raising and knowledge sharing.[355]

The International Nitrogen Initiative (INI) is another group that works on the nitrogen challenge. It was established to bring together scientists, policymakers, governments, and stakeholders to start and maintain discussions on optimizing nitrogen use in food production and minimizing the impact of excess nitrogen.[356]

Support to increase food security

Several multilateral initiatives that focus on the intersection of food security and climate change can provide support for scaling up N_2O solutions. For example, the Mitigation of Climate Change in Agriculture (MICCA) Programme bridges the UN Food and Agriculture Organizations' work on climate change and agriculture with the UNFCCC.[357] The MICCA Programme provides technical support to monitor and assess GHG emissions and the mitigation potential in agriculture, develops the capacity of stakeholders working on national GHG inventories and of farmers using climate-smart agriculture, carries out LCAs of mitigation practices to guide decision-making, and gives guidance on climate change mitigation and adaptation options.[358]

The Consultative Group for International Agricultural Research (CGIAR) is implementing the Research Program on Climate Change, Agriculture, and Food Security (CCAFS) that focuses on solutions for food security within the context of a changing climate. Its priority research themes are climate-smart technologies and practices, low emissions development, climate services and safety nets, gender and social inclusion, and scaling up climate-smart agriculture.[359]

With guidance, these support programs may be directed toward food systems solutions that also benefit the climate by reducing N_2O emissions from agricultural operations. Further, their experience in the agriculture sector could provide insight in developing a global or regional agricultural N_2O mitigation strategy.

Appendix C: Calculations of N_2O emissions

Understanding units and metrics used for N_2O emissions

To better understand and compare the contribution of different GHGs, scientists use a standardized measurement called carbon dioxide equivalent (CO_2e). The calculation of CO_2e includes the amount of the gas multiplied by its global warming potential (GWP), relative to CO_2, over a defined period of time. For example, GWP100 indicates a 100-year span, and the GWP_{100} of CO_2 is 1. The GWP_{100} of N_2O as determined by the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) is 273. This means that N_2O over a span of 100 years contributes 273 times the amount of warming as the same amount of CO_2. The GWP_{20} of N_2O is also 273, which shows that this climate pollutant quickly damages the climate after it is emitted. These measurements are expressed in either megatons (Mt) or gigatons (Gt) of CO_2e.Unless otherwise indicated, N_2O emissions in this *Primer* are converted to CO_2e from megatons (Mt) of N_2O using the IPCC-determined $GWP_{100} = 273$ for N_2O.

In the scientific literature, emissions may be reported in terms of the mass of nitrogen as N_2O (N-N_2O). These values are converted to emissions of N_2O by multiplying by a conversion factor of 1.57:

$$\frac{molar\ mass\ of\ N_2O}{molar\ mass\ of\ 2\ N\ atoms} = \frac{44}{2\times(14)} = 1.57$$

Unless otherwise indicated, N_2O emissions in this *Primer* are converted to CO_2e from megatons (Mt) of N_2O using the IPCC-determined $GWP_{100} = 273$ for N_2O.

In the scientific literature, emissions may be reported in terms of the mass of nitrogen as N_2O (N-N_2O). These values are converted to emissions of N_2O by multiplying by a conversion factor of 1.57.

Appendix D: Acronyms and abbreviations

4R	right source, right rate, right time, right place
AR6	Sixth Assessment Group
BECCS	bioenergy with carbon capture and storage
CAD	Canadian dollar
CBAM	Carbon Border Adjustment Mechanism
CCAC	Climate and Clean Air Coalition
CCAFS	Consultative Group for International Agricultural Research
CFC	chlorofluorocarbon
CGIAR	Consultative Group for International Agricultural Research
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	Conference of the Parties
EEAP	Environmental Effects Assessment Panel
EPA	Environmental Protection Agency
ETS	Emissions Trading System
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GHG	greenhouse gas
Gothenburg Protocol	Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-Level Ozone
Gt	gigaton or gigatonne
GPNM	Global Partnership on Nutrient Management
GWP	global warming potential
H_2	hydrogen gas
HFC	hydrofluorocarbon
IGSD	Institute for Governance & Sustainable Development
INCOM	Interconvention Nitrogen Coordination Mechanism
INI	International Nitrogen Initiative
INMS	International Nitrogen Management System
IPCC	Intergovernmental Panel on Climate Change
IWG	Inter-Agency Working Group
kg	kilogram
KGML-ag	knowledge-guided machine learning model for agroecosystems
LCA	life cycle assessment
LRTAP	Convention on Long-Range Transboundary Air Pollution
Locus ag	Locus Agricultural Solutions
MeBr	methyl bromide
MICCA	Mitigation of Climate Change in Agriculture
Mt	megaton or megatonne
Montreal Protocol	Montreal Protocol on Substances that Deplete the Ozone Layer

MEA	Multilateral Environmental Agreement
N	nitrogen
NACAG	Nitric Acid Climate Action Group
NDC	Nationally Determined Contribution
NO_x	nitrogen oxide
N_r	reactive nitrogen
N_2O	nitrous oxide
$PM_{2.5}$	fine particulate matter
ppb	parts per billion
ODS	ozone-depleting substance
SCM	SOP COCUS MAIZE+
SLCP	short-lived climate pollutant
SAP	Scientific Assessment Panel
SOP	Save Our Planet
t	ton or tonne
TEAP	Technology and Economic Assessment Panel
TFRN	Task Force on Reactive Nitrogen
UN	United Nations
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
US$	United States dollar
UV	ultraviolet (radiation)
VRT	variable rate technology
yr	year

References

[1] Forster P., *et al.* (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, 7–125 (*see* Table 7.15 on the emission metrics for a select species of gases, including methane and nitrous oxide (N_2O).).

[2] IGSD's research confirms that decarbonization focused on phasing out fossil fuel use alone is insufficient to slow near-term warming to keep the world within reach of the 1.5 °C and below the more dangerous 2 °C guardrail, and that the fastest and most effective strategy is to combine the marathon to zero out carbon dioxide (CO_2) emissions from decarbonizing the energy system with the sprint to rapidly cut non-CO_2 super climate pollutants and protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH_4), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O). *See generally* Institute for Governance & Sustainable Development (June 2024) *The Need for Fast Near-Term Climate Mitigation to Slow Feedbacks and Tipping Points: Critical Role of Short-lived Super Climate Pollutants to Address the Climate Emergency*.

[3] NOAA Climate.gov (2021) *Climate Forcing* (last accessed 19 September 2024).

[4] World Meteorological Organization (2019) GLOBAL OZONE RESEARCH AND MONITORING PROJECT, REPORT NO. 58, *Scientific Assessment of Ozone Depletion: 2018*, 1.61 ("As a result of this growth, the contribution of N_2O to radiative forcing has continued to rise, reaching 0.19 W m^{-2} in 2016, approximately 10% that of CO_2."). N_2O emissions have continued to grow since 2019, increasing its contribution to radiative forcing; for the most recent estimate, *see* Forster P. M., *et al.* (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2634 (*see* Table 3 *showing* "Contributions to anthropogenic effective radiative forcing (ERF) for 1750–2023 assessed in this section." For N_2O, reported values are 0.22 [0.19 to 0.26] W m^{-2}).

[5] Intergovernmental Panel on Climate Change (2023) *Climate Change 2023: Synthesis Report*, Contribution of Working Groups I, II, III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, Lee H. & Romero J. (eds.), 4 (*see* footnote 8 *stating* that "[c]ontributions from emissions to the 2010–2019 warming relative to 1850–1900 assessed from radiative forcing studies are: CO_2 0.8 [0.5 to 1.2]°C; methane 0.5 [0.3 to 0.8]°C; nitrous oxide 0.1 [0.0 to 0.2]°C and fluorinated gases 0.1 [0.0 to 0.2]°C").

[6] Intergovernmental Panel on Climate Change (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE.", 807 ("In most regions, CH_4 and N_2O emission are both lower in mitigation pathways that limit warming to 3°C (>50%) or lower (C1–C6) compared to scenarios with < 4°C (Popp et al. 2017; Rogelj et al. 2018a)."); *see also* Rogelj J. & Lamboll R. D. (2024) *Substantial reductions in non-CO_2 greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget*, COMMUNICATIONS EARTH & ENVIRONMENT 5:35, 2–3 ("Starting from the latest IPCC compilation of internally consistent mitigation scenarios15 we estimate RCBs as in IPCC AR6 (see Supplementary Tables S1 and S2) and present the accompanying non-CO_2 assumptions. RCB estimates require deep reductions in non-CO_2 greenhouse gases (Table 1). RCB estimates in line with limiting warming to 1.5 °C assume 1.5 °C-compatible CH_4 reductions from 2020 to 2050 of 51% (47–60%, range between 25th and 75th quantile regressions at 1.5 °C of global warming across scenarios, see Fig. 1, panel a). These reductions change to 44% (39–53%) and 34% (27–43%) for RCBs in line with limiting warming to 1.7 °C and 2.0 °C, respectively. Global N_2O emissions are also limited, with a reduction of 22% (7–35%) between 2020 and 2050 for 1.5 °C-compatible RCBs, and reductions of 18% (3–30%) and 11% (1% increase–23%) for 1.7 °C and 2 °C-compatible RCBs, respectively. In all cases, these CH_4 and N_2O reductions represent marked global emission reduction efforts.").

[7] World Meteorological Organization (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 99 ("In particular, the accelerating increase of N_2O abundances and emissions is a serious threat for stratospheric ozone, as it is the main driver of NO_x-induced ozone depletion and by far the most abundant ODS (Ravishankara et al., 2009; Müller et al.,

2021). To illustrate these effects, we here use the maximum range of potential N_2O ODPs from 0.015 to 0.030 as derived by Revell et al. (2015) for various atmospheric scenarios between the years 2000 and 2100. When deriving CFC-11-equivalent emissions from this range, we estimate between 461 and 922 Gg yr^{-1} for 2020, i.e., 5–10 times the ODP-weighted emissions from all CFCs in that year. In addition, the increase in N_2O emissions translates to an increase of 52–104 Gg of CFC-11 equivalent emissions between 2016 and 2020.").

[8] United Nations Environmental Programme (2023) ENVIRONMENTAL EFFECTS OF STRATOSPHERIC OZONE DEPLETION, UV RADIATION, AND INTERACTIONS WITH CLIMATE CHANGE: 2022 ASSESSMENT REPORT, 4, 181 ("The concurrence of heat waves with drought and high UV-B irradiance (280-315 nm) may negatively affect food security and biodiversity of crops and animals. These climatic conditions can disrupt formerly favourable habitats and may shift habitats to locations with different conditions, to which plants and animals may not be adapt. Tropical coral reefs under naturally high UV irradiance are of particular concern, since an increase in sea surface temperatures of 1 °C to 2 °C can cause bleaching of corals, enhanced by high amounts of UV radiation."; "Available evidence suggests that current levels of UV-B radiation in the tropics can alter the morphology (e.g., smaller leaves, reduced shoot height) and chemistry (e.g., increased flavonoid levels) of native, non-crop tropical plants, but that biomass production is rarely decreased in these species (e.g., [290]). By comparison, several field experiments have shown that certain varieties of temperate-zone crops (e.g., wheat and soybean) [291-293] show decreases in photosynthesis and yield when grown under ambient UV-B radiation in the tropics. These findings suggest that some important crop species grown in the tropics might be vulnerable to relatively small increases in UV-B radiation."). *See also* Bornman J. F., Barnes P. W., Robson T. M., Robinson S. A., Jansen M. A. K., Ballaré C. L., & Flint S. D. (2019) *Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems*, PHOTOCHEM PHOTOBIOL SCI 18(3): 681–716.

[9] World Meteorological Organization (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 99 ("Several recent publications have found that global N_2O emission increases have been accelerating over the last two decades and by now exceed some of the highest projections (Thompson et al., 2019; Tian et al., 2020; IPCC, 2021)."). *See also* National Oceanic and Atmospheric Administration (5 April 2024) *No sign of greenhouse gases increases slowing in 2023* ("In 2023, levels of nitrous oxide, the third-most significant human-caused greenhouse gas, climbed by 1 ppb to 336.7 ppb. The two years of highest growth since 2000 occurred in 2020 (1.3 ppb) and 2021 (1.3 ppb).").

[10] World Meteorological Organization (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 99 ("Anthropogenic emissions N_2O were driving that increase, and these alone (43%, Tian et al., 2020) were equal to more than two times the ODP-weighted emissions from all CFCs in 2020. For context, when compared to the CFC emission peak from 1987, those 2020 anthropogenic N_2O emissions were equal to more than 20 % the ODP-weighted emissions from CFCs in that year.").

[11] United Nations Development Programme (UNEP) & Food and Agriculture Organization of the United Nations (FAO) (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 17 ("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)").

[12] Hasanbeigi A. & Sibal A. (2023) STOPPING A SUPER-POLLUTANT: N_2O EMISSIONS ABATEMENT FROM GLOBAL ADIPIC ACID PRODUCTION, Global Efficiency Intelligence, 2 ("There are estimated to be 39 operational facilities globally producing adipic acid while almost two thirds of the global adipic acid production takes place in China and U.S. Adipic acid production is one of the largest sources of nitrous oxide (N_2O) emissions."); 9 ("Global facilities are currently abating N_2O emissions at different rates. Our key assumptions for the current abatement rates are as follow[s]: ● U.S. adipic acid production: There are two adipic acid producers in the U.S. One reported to abate N_2O emissions at 97-99% rate in the last 5 years. We assumed a 98% abatement rate for this facility. The other plant's baseline abatement rate was assumed at 80%, which reflects a 5-year average (ClimeCo Corporation, 2019). ● Chinese adipic acid production: There are 11 producers of adipic acid in China. Several reports, in addition to expert testimony,

led to the conclusion that Chinese adipic acid producers are not utilizing N_2O abatement technology (U.S. EPA, 2019, McKenna et al., 2020, Qing et al., 2020). ● Other countries' adipic acid production: For all other producers including Brazil, Japan, South Korea, France, Germany, and Italy we assumed abatement of 98% of N_2O emissions."). *As reported in* McKenna P. (1 May 2023) *Eleven Chemical Plants in China and One in the U.S. Emit a Climate Super-Pollutant Called Nitrous Oxide That's 273 Times More Potent Than Carbon Dioxide*, INSIDE CLIMATE NEWS ("Neither the U.S. nor China require adipic acid manufacturers to reduce their nitrous oxide emissions."). *See also* McKenna P., Pike L., & Northrop K. (6 August 2020) *'Super-pollutant' emitted by 11 Chinese chemical plants could equal a climate catastrophe*, INSIDE CLIMATE NEWS ("Eleven adipic acid plants in China produce nearly half of the world's adipic acid… an Inside Climate News investigation, based on dozens of interviews and a review of hundreds of pages of documents from the Chinese government, the United Nations, and Chinese state media, strongly suggests that when funding for the U.N. program ended, so too did nearly all of the emissions reductions. This likely occurred despite the availability of proven, low-cost abatement technology. If the vast majority of the plants' emissions are released, unabated into the atmosphere, their collective emissions would exceed the yearly greenhouse gas emissions from all passenger vehicles in California, the most populous state in America, as well as the emissions from all cars in Beijing and Shanghai, China's two largest megacities.").

[13] UNEP & FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 22 ("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)"); 134 ("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.").

[14] U.S. Environmental Protection Agency (U.S. EPA) (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, at 28 ("The global abatement potential is 231 $MtCO_2e$, or 86% of projected emissions in 2030.").

[15] Winiwarter W., et al. (2018). Technical Opportunities to Reduce Global Anthropogenic Emissions of Nitrous Oxide, ENVTL. RES. LETTERS, 13:1–12, 3, tbl. 1.

[16] U.S. Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis*. *See also* McKenna P. (26 September 2024) *Focus on the 'Forgotten Greenhouse Gas' Intensifies as All Eyes Are on the U.S. and China to Curb Pollution*, INSIDE CLIMATE NEWS ("The two exceptions are the United States and China, which together are responsible for approximately 80 percent of the world's nitrous oxide emissions from the industrial sector. The emissions come primarily from the production of adipic acid, a precursor to high-strength nylon, and nitric acid, used in fertilizer production…. Duke and John Podesta, Biden's senior advisor for international climate policy, traveled to Beijing in late August and early September to continue bilateral discussions with China to reduce methane and other "non-CO2" greenhouse gases, including nitrous oxide. "We are deep in conversation with China," Duke said. "We will continue to push for rapid progress to reduce those emissions." Following the visits, China's Ministry of Ecology and Environment held a workshop on opportunities to address nitrous oxide emissions, including industrial pollution.").

[17] UNEP & FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 20 ("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)").

[18] UNEP & FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 23 ("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)"). *See also* Winiwarter W., *et al*. (2018) *Technical Opportunities to Reduce Global Anthropogenic Emissions of Nitrous Oxide*, ENVIRON. RES. LETT. 13:1–12, 3, tbl. 1 (providing an overview of N_2O emission abatement technology implemented in GAINS); *and* Hassan M., *et al.* (2022) *Management Strategies to Mitigate N_2O Emissions in Agriculture,* LIFE 12(3), 439 ("The relationships between N_2O occurrence and factors regulating it are an important premise for devising mitigation strategies. Here, we evaluated various options in the literature and found that N_2O emissions can be effectively reduced by intervening on time and through the method of N supply (30–40%, with peaks up to 80%), tillage and irrigation practices (both in non-univocal way), use of amendments, such as biochar and lime (up to 80%), use of slow-release fertilizers and/or nitrification inhibitors (up to 50%), plant treatment with arbuscular mycorrhizal fungi (up to 75%), appropriate crop rotations and schemes (up to 50%), and integrated nutrient management (in a non-univocal way).").

[19] Methyl Bromide is a controlled substance under the Montreal Protocol, added in 1992 to Annex E, Controlled Substances, Group 1, via the Copenhagen Amendment to the Montreal Protocol. *See also* UNEP (2014) *Phasing-Out Methyl Bromide in Developing Countries: A success story and its challenges*, at 5 ("A major barrier when introducing alternatives was that this process often had to be carried out against the background of an established system, with infrastructure, equipment, and supply chains already in place. In the agricultural sector, there are large numbers of farmers and different crops scattered across countries. The process followed for selecting the most suitable alternatives, where these were first trialed and demonstrated, and where key stakeholders were involved, contributed to creating a good level of acceptance towards the alternatives proposed. A wide approach is necessary, including registration and commercial availability of successful alternatives, at a feasible cost. Training was an essential component of the phase-out process, and should be continued.").

[20] UNEP (2013) DRAWING DOWN N_2O TO PROTECT CLIMATE AND THE OZONE LAYER, ix ("Two-thirds of current anthropogenic N_2O emissions originate from agriculture and these can be reduced by boosting nitrogen use efficiency, especially by making the use of fertilizer, manure and feed more efficient. Improving nitrogen use efficiency can be accomplished through a wide variety of feasible options. This would bring added benefits of higher crop and livestock productivity, lower required agriculture inputs, as well as reduced air and water pollution due to decreased nitrogen losses to the environment."). *See also* Soil Association (2020) *Fixing Nitrogen: The challenge for climate, nature, and health*, 13 ("When there is a surplus of nitrogen, some plants and fungi do better than others. Nitrogen-tolerant species such as nettles and hemlock thrive with these high nutrient levels to the detriment of more sensitive species, reducing wildlife diversity. The impact of excess nitrogen levels is being felt in protected habitats (such as marshes, bogs, meadows and woods) where nitrogen is not routinely applied but reaches habitats through atmospheric deposition. Reactive nitrogen is soluble and therefore easily makes its way into and through water systems. Increased levels of nutrients in watercourses encourage plant growth, particularly those such as algae. These 'algal blooms' reduce light and oxygen levels in water, a process known as eutrophication, which alters plant communities, kills fish and has effects all the way up the marine and freshwater food chains.").

[21] UNFCCC Secretariat (2021) *Nationally determined contributions under the Paris Agreement, Synthesis report by the secretariat*, ¶ 5(d) ("Parties have increased the coverage of sectors and GHGs: 99.2 per cent of their total GHG emissions are covered compared with 97.8 per cent for the previous NDCs; and all cover CO_2 emissions, almost all cover CH_4 and N_2O emissions, most cover HFC emissions and many cover PFC, SF_6 and NF_3 emissions."; *see* Footnote 3 for the definition of 'almost all': 'almost all' for more than 90 per cent.").

[22] Sutton M. A., Howard C. M., Mason K. E., Brownlie W. J., & Cordovil C. M. d. S. (2022) *Nitrogen Opportunities for Agriculture, Food & Environment. UNECE Guidance Document on Integrated Sustainable Nitrogen Management*, ii, 1 ("Apart from ammonia (NH_3), this has meant considering emissions of nitrogen oxides (NOx) and nitrous oxide (N_2O) to air, alongside nitrate (NO_3^-) and other reactive nitrogen (Nr) losses to water. … Under the emerging 'joined-up' approach to nitrogen, we realise that the synergies are critical, since they provide win-wins that can help mobilize action."; "The present guidance document is focused on agriculture in the context of the food system, and includes specific information on the principles and measures that can reduce emissions to the air of ammonia (NH_3), nitrogen oxides (NOx), nitrous oxide (N_2O) and N_2, plus nitrate (NO_3^-) and other Nr leaching to water and total N loss.").

[23] Donner L., and Ramanathan V. (1980) *Methane and Nitrous Oxide: Their Effects on the Terrestrial Climate*, J. ATMOS. SCI. 37:119–124, 119 ("From the energy balance calculations, it is concluded that the longwave opacity (i.e., the so-called "greenhouse effect") due to present-day observed concentrations of CH_4 and N_2O contribute nearly 2 K to hemispheric mean surface temperature with possible larger contributions to polar surface temperatures.").

[24] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2546 ("Anthropogenic sources contributed 35% to the total N_2O emissions (6.5, 3.2–10.0TgN yr^{-1}).").

[25] NOAA Research (2024) *Nitrous oxide emissions grew 40 percent from 1980 to 2020, accelerating climate change* (last visited on 13 Sept 2024) ("Ice core records show that N2O concentrations remained relatively constant at about 270 parts per billion over the past 2,000 years, but concentrations began going up around 1750.").

[26] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16 :2543–2604, 2545 ("According to BU estimates, the increase in global N_2O emissions was primarily due to a 40% increase in anthropogenic emissions from 4.8 (3.1–7.3) Tg yr^{-1} in 1980 to 6.7 (3.3–10.9)Tg yr^{-1} in 2020.").

[27] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2545, 2550 ("Among all anthropogenic sources, direct agricultural emissions made the largest contribution, increasing from 2.2 (1.6–2.8) $TgNyr^{-1}$ in 1980 to 3.9 (2.9–5.1) $TgNyr^{-1}$ in 2020. The concurrent indirect agricultural N_2O emissions also steadily increased from 0.9 (0.7–1.1) to 1.3 (0.9–1.6) $TgNyr^{-1}$."; "[I]ndirect emissions from anthropogenic nitrogen additions, which includes atmospheric nitrogen deposition (NDEP) on the land, atmospheric NDEP on the ocean, and the effects of anthropogenic loads of reactive nitrogen in inland waters, estuaries, and coastal vegetation[.]").

[28] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget 1980–2020*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2545–2546 ("Unlike anthropogenic emissions, global natural land and ocean N_2O emissions were relatively stable. According to the BU approaches, the total amount of global natural N_2O emissions fluctuated between 11.7 and 12.1 $Tgyr^{-1}$ during 1980–2020. Among all sources, natural emissions from shelves, inland waters, and lightning and atmospheric production were assumed to be constant during 1980–2020. According to BU approaches, the total natural emissions from these sources were 1.8 (1.03.0) $TgNyr^{-1}$.").

[29] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2546 ("Anthropogenic sources contributed 35% to the total N_2O emissions (6.5, 3.2–10.0TgN yr^{-1}).").

[30] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2564–2565 (*see* Table 3 on the global N_2O budget (in TgN yr^{-1}) for the 1980s, the 1990s, the 2000s, the 2010s, and the year 2020; "In this study, N_2O fluxes are expressed in teragrams of N_2O-N per year, where 1 TgN_2O-N yr^{-1} (1 TgN yr^{-1})=10^{12} gN_2O-N yr^{-1}=1.57 x 10^{12} g N_2O yr^{-1}, with change rates in N_2O fluxes expressed in teragrams of nitrous oxide-nitrogen per year squared (TgN yr^{-2}), representing the first derivative of annual N_2O fluxes calculated by the linear regression method."). *Note* that perturbed fluxes are not included in the total (gross) N_2O emissions presented in this *Primer*.

[31] Estimate per U.S. EPA Greenhouse Gas Equivalencies Calculator.

[32] UNEP & FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 20–21 (“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)”).

[33] Lan X., Thoning K. W., and Dlugokencky E. J. (2024) *Trends in globally-averaged CH_4, N_2O, and SF_6 determined from NOAA Global Monitoring Laboratory measurements*, Version 2024-08 (*last accessed* 27 August 2024). *See also* Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2547 (“Atmospheric N_2O mole fractions have increased by nearly 25% since the preindustrial era, from 270 ppb (parts per billion) in 1750 (MacFarling Meure et al., 2006) to 336 ppb in 2022, and have shown an increase of 35 ppb (10 %) since 1980 (Fig. 2). The current mole fraction is higher than at any time in the last 800 000 years (Schilt et al., 2010).”).

[34] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2569 (“Emissions from other direct anthropogenic sources (including fossil fuel and industry, waste and wastewater, and biomass burning), which decreased from 0.51 $TgNyr^{-1}$ in 1980 to 0.18 $TgNyr^{-1}$ in 2020, made the largest contribution to the decreasing trend in N_2O emissions from Europe.”).

[35] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2569 (“Direct agricultural emissions and indirect emissions show overall decreasing trends from 0.46 and 0.16 $TgNyr^{-1}$ in 1980 to 0.38 and 0.12 $TgNyr^{-1}$ in 2020, respectively, mainly due to a reduction in fertilizer use after the collapse of the Soviet Union (Tian et al., 2022). However, the decreasing trend in direct agricultural emissions has leveled off since the 2000s.”).

[36] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2571 (“China’s total N_2O emissions increased from 0.76 $TgNyr^{-1}$ in 1980 to 1.38 $TgNyr^{-1}$ in 2020. Direct emissions from N additions in agriculture made the largest contribution to the increase in China’s N_2O emissions, which increased from 0.29 $TgNyr^{-1}$ in 1980 to 0.71 $TgNyr^{-1}$ in 2016 and then decreased to 0.64 $TgNyr^{-1}$ in 2020 due to decreased N fertilizer application (Fig. 14). Both indirect emissions and other direct emissions continuously increased, from 0.09 and 0.11 $TgNyr^{-1}$ in 1980 to 0.24 and 0.27 $TgNyr^{-1}$ in 2020, respectively.”).

[37] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2571 (“The total anthropogenic N_2O emissions from China increased at an average rate of $18.9\times10{-}3$ $TgNyr^{-2}$ during 1980–2020, which was the largest among the 18 regions and contributed 40% of the increase in global anthropogenic N_2O emissions.”).

[38] Ravishankara A. R., Daniel J. S., & Portmann R. W. (2009) *Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century*, SCIENCE 326:123–125, (“The primary source of stratospheric NO_x is surface N_2O emissions [(7) and references therein]. N_2O has been thought of as primarily a natural atmospheric constituent, but the influence of its changes on long-term changes in ozone concentrations has also been examined (8–10). Nitrous oxide shares many similarities with the CFCs, historically the dominant ODSs. The CFCs and N_2O are very stable in the troposphere, where they are emitted, and are transported to the stratosphere where they release active chemicals that destroy stratospheric ozone through chlorine- or nitrogen oxide–catalyzed processes. They both have substantial anthropogenic sources. Unlike CFCs, N_2O also has natural sources, akin to methyl bromide, which is another important ODS. Assigning an ODP for N_2O and separating out the natural and anthropogenic emissions are therefore no more conceptually difficult than they are for methyl bromide.”).

[39] World Meteorological Organization (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 99 ("Anthropogenic emissions N_2O were driving that increase, and these alone (43%, Tian et al., 2020) were equal to more than two times the ODP-weighted emissions from all CFCs in 2020. For context, when compared to the CFC emission peak from 1987, those 2020 anthropogenic N_2O emissions were equal to more than 20 % the ODP-weighted emissions from CFCs in that year.").

[40] Butler A. H., Daniel J. S., Portmann R. W., Ravishankara A. R., Young P. J., Fahey D. W., & Rosenlof K. H. (2016) *Diverse policy implications for future ozone and surface UV in a changing climate*, ENVTL. RES. LETTERS 11:064017, 6 ("Reducing greenhouse gas emissions to at least the RCP 4.5 trajectory is required to obtain the goals set forth by COP 21, which aim to limit global temperature changes to less than 2 °C above pre-industrial levels (Collins et al 2013). If achieved, this would also return stratospheric ozone and UV to near historical levels globally by 2100. If we aim to limit global temperature changes to less than 1.5 °C CO_2, CH_4, and N_2O all need to be reduced to near RCP 2.6 levels, which would also benefit the ozone layer.").

[41] Weber J., Keeble J., Abraham N. L., Beerling D. J., & Martin M. V. (2024) *Global agricultural N_2O emission reduction strategies deliver climate benefits with minimal impact on stratospheric O_3 recovery*, NPJ CLIM. ATMOS. SCI. 7(1): 1–9, 1 ("We calculate a N_2O emission reduction of 1.35 TgN_2Oyr^{-1} (~5% of 2020 emissions) using spatially separate deployment of nitrification inhibitors ($70–113 tCO_2e^{-1}) and crushed basalt (no-cost co-benefit) which also sequesters CO_2. In Earth System model simulations for 2025–2075 under high (SSP3-7.0) and low (SSP1-2.6) surface warming scenarios, this N_2O mitigation reduces NO_x-driven O_3 destruction, driving regional stratospheric O_3 increases but with minimal impact on total O_3 column recovery. By 2075, the radiative forcing of the combined N_2O and CO_2 reductions equates to a beneficial 9–11 ppm CO_2 removal. Our results support targeted agricultural N_2O emission reductions for helping nations reach net-zero without hindering O_3 recovery.").

[42] Forster P., *et al.* (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, 7–125 (*see* Table 7.15 on the emission metrics for a select species of gases, including methane and nitrous oxide (N_2O).).

[43] UNEP & FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 16 ("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)"); 89 ("6. Without additional actions, nitrous oxide emissions would lead to around 0.2º C 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 0.1º C reduction in warming beginning late in this century.").

[44] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040[.] … In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%].").

[45] Lenton T. M., *et al.* (eds.) (2023) *Earth System Tipping Points, in* GLOBAL TIPPING POINTS REPORT 2023, 51 ("We identify more than 25 parts of the Earth system that have tipping points, based on evidence from paleoclimate records, observations, theory and complex computer models, including: In the cryosphere, evidence exists for large-scale tipping points in Greenland and Antarctic ice sheets, and for localised tipping in glaciers and permafrost. In the biosphere, tipping points are present in a variety of ecosystems, including Amazon forest dieback, savanna and dryland degradation, lake eutrophication, coral reef and mangrove die-offs, and the collapse of some fisheries. In ocean-atmosphere circulations, there is evidence for tipping points in Atlantic and Southern Oceans overturning, as well as for the West African monsoon."). *See also* Lenton T. M., et al. (eds.) (2023) Summary Report, in GLOBAL TIPPING POINTS REPORT 2023, 13 ("Already, at today's 1.2°C global warming, tipping of warm-water coral reefs is likely and we cannot rule out that four other systems may pass tipping points: the ice sheets of Greenland and West Antarctica, the North Atlantic's Subpolar Gyre circulation, and parts of the permafrost subject to abrupt thaw. … Passing 1.5°C global warming, widespread mortality in warm-water coral reefs becomes very likely, and another three potential tipping systems start to become vulnerable: boreal forest, mangroves and seagrass meadows.").

[46] Bao T., Jia G., & Xu X. (2023) *Weakening greenhouse gas sink of pristine wetlands under warming*, NATURE CLIMATE CHANGE 13, 462–469, 464, 466 ("Warming also enhanced the wetland N_2O source by 18%. Warming increased N_2O emissions only at vascular plant sites (19%; Fig. 3a, c), and across all four PFTs, the N_2O emissions of only the graminoid sites (27%) were stimulated by warming (Fig. 3b, d). Although ecosystem types are considered to play an important role in determining local carbon and nitrogen exchange, our meta-analysis revealed no significant ($P > 0.05$) GHG response to warming across various wetland types (Extended Data Fig. 2)."; "Warming only strengthens the N_2O source markedly at vascular plant sites (Fig. 3). N_2O is produced primarily from nitrification and denitrification, two microbial-driven processes dependent on available substrates [22]. Warming accelerates nitrogen mineralization, enhances the use of mineral nitrogen and promotes the secretion of phytohormones into the rhizosphere of vascular plants, where nitrifying and denitrifying bacteria accumulate and N_2O production is enhanced [43].").

[47] Yuan Y., Zhuang Q., Zhao B., & Shurpali N. (2023) *Nitrous oxide emissions from pan-Arctic terrestrial ecosystems: A process-based biogeochemistry model analysis from 1969 to 2019*, EGUSPHERE, *preprint*, 1 ("We find that both regional N_2O production and net emissions increased from 1969 to 2019, with production ranging from 1.2–1.3 Tg N yr^{-1} and net emissions from 1.1–1.2 Tg N yr^{-1} considering the permafrost thaw effects. Soil N_2O uptake from the atmosphere was 0.1 Tg N yr^{-1} with a small interannual variability. Atmospheric N deposition significantly increased N_2O emission by 31.5 ± 3.1 %. Spatially, terrestrial ecosystems act as net sources or sinks ranging from -12 to 700 mg N m^{-2} yr^{-1} depending on temperature, precipitation, soil characteristics, and vegetation types in the region.").

[48] Voigt C., Maruschak M. E., Lamprech R. E., Jackowicz-Korczyynski M., Lindgren A., Mastepanov M., Granlund L., Christensen T. R. Tahvanainen T., Martikainen P. J., & Biasi C. (2017) *Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw*, PROCEEDINGS OF THE NAT'L. ACAD. OF SCIENCES, 114(24):6238–6243, 6283 ("We show that regions with high probability for N_2O emissions cover one-fourth of the Arctic.").

[49] Maruschak M. E., *et al.* (2021) *Thawing Yedoma permafrost is a neglected nitrous oxide source*, NATURE COMMS. 12(7107):2, 5 ("Our field flux measurements revealed substantial N_2O release from Yedoma permafrost following thaw. At the Kurungnakh exposure, the N_2O fluxes from thawed Yedoma surfaces were highly variable (63 (–19–6286) μg N m^{-2} day^{-1}; median with (range)), at the high-end exceeding the typical fluxes from permafrost-affected soils (38 (6–189) μg N m^{-2} day^{-1}; median with (25^{th}–75^{th} percentiles); ref. 6) by two orders of magnitude."; "On Kurungnakh the net N mineralization rates were higher in Yedoma revegetated with grasses than in bare freshly thawed Yedoma (Fig. 3b, Supplementary Table 3). The negative net N mineralization, i.e., net N immobilization, in freshly thawed Yedoma can be explained by high uptake of mineral N species into microbial biomass, exceeding the rate of N liberated from organic matter. In contrast, high net N transformation rates in revegetated Yedoma indicate that the microbial needs for mineral N are well met as a result of continued mineralization after thaw, which allows N_2O emissions to occur even in the presence of plant N uptake."; "By using a targeted metagenomics tool designed to capture the genes responsible for key functions of the N cycle (Ref. 45; see Methods), we here reveal another important mechanism driving the increase in N_2O emissions with time after thaw: changes in microbial community composition.

We observed significant changes across the Yedoma exposure in the relative abundance of nitrification and denitrification genes with time passed after thaw, associated drainage and plant colonization (Fig. 4, Supplementary Fig. 8). These changes occurred within just a couple of years and led to strikingly different microbial community structure related to N cycling in thawed Yedoma compared to the Holocene cover deposits that feature well-developed cryosols prevailing in the region.").

[50] Wilkerson J., Dobosky R., Sayres D. S., Healy C., Dumas E., Baker B., & Anderson J. G. (2019) *Permafrost nitrous oxide emissions observed on a landscape scale using the airborne eddy-covariance method*, ATMOS. CHEM. PHYS. 19(7): 4257–4268, 4257 ("The microbial by-product nitrous oxide (N_2O), a potent greenhouse gas and ozone depleting substance, has conventionally been assumed to have minimal emissions in permafrost regions. This assumption has been questioned by recent in situ studies which have demonstrated that some geologic features in permafrost may, in fact, have elevated emissions comparable to those of tropical soils. However, these recent studies, along with every known in situ study focused on permafrost N_2O fluxes, have used chambers to examine small areas (< 50 m^2). In late August 2013, we used the airborne eddy-covariance technique to make in situ N_2O flux measurements over the North Slope of Alaska from a low-flying aircraft spanning a much larger area: around 310 km^2. We observed large variability of N_2O fluxes with many areas exhibiting negligible emissions. Still, the daily mean averaged over our flight campaign was 3.8 (2.2–4.7) mg N_2O m^{-2} d^{-1} with the 90 % confidence interval shown in parentheses. If these measurements are representative of the whole month, then the permafrost areas we observed emitted a total of around 0.04–0.09 g m^{-2} for August, which is comparable to what is typically assumed to be the upper limit of yearly emissions for these regions."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61(e2021RG000757): 1–81, 23 ("Emissions of nitrous oxide—another potent greenhouse gas—from permafrost also may be non-negligible (Voigt et al., 2020; Wilkerson et al., 2019) and require further study. In general, improved projections of hydrological changes within the permafrost region (Andresen et al., 2020) and better quantification of the rates of permafrost organic carbon mineralization into CO_2 versus CH_4 (or other greenhouse gases such as N_2O), and the fate of permafrost C exported as dissolved organic matter in aquatic environments remain active areas of study with major climate implications (J. C. Bowen et al., 2020; Laurion et al., 2020; Zolkos & Tank, 2020)").

[51] Schaefer K., Lantuit H., Romanovsky V. E., Schuur E. A. G., & Witt R. (2014) *The Impact of the Permafrost Carbon Feedback on Global Climate*, ENVIRON. RES. LETT. 9(085003): 1–9, 2 ("If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO_2) and methane (CH_4) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions … The PCF is irreversible on human time scales because in a warming climate, the burial mechanisms described above slow down or stop, so there is no way to convert CO_2 into organic matter and freeze it back into the permafrost."). *See also* Schaefer K., Zhang T., Bruhwiler L., & Barrett A. P. (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS B 63(2): 165–180, 166 ("The permafrost carbon feedback (PCF) is an amplification of surface warming due to the release into the atmosphere of carbon currently frozen in permafrost (Fig. 1). As atmospheric CO_2 and methane concentrations increase, surface air temperatures will increase, causing permafrost degradation and thawing some portion of the permafrost carbon. Once permafrost carbon thaws, microbial decay will resume, increasing respiration fluxes to the atmosphere and atmospheric concentrations of CO_2 and methane. This will in turn amplify the rate of atmospheric warming and accelerate permafrost degradation, resulting in a positive PCF feedback loop on climate (Zimov et al., 2006b).").

[52] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 26 ("Current-generation climate models suggest a net positive impact of the permafrost carbon-climate feedback on global climate with estimates of additional warming of 0.05-0.7°C by 2100 (Schaefer et al., 2014, Burke et al., 2018, Kleinen and Brovkin, 2018, Nitzbon et al., 2023) based on low- to high-emissions scenarios, respectively. Methane emissions from permafrost could temporarily contribute up to 50 per cent of the permafrost-induced radiative forcing due to its higher warming potential (Walter Anthony et al., 2016, Turetsky et al., 2020, Miner et al., 2022). Overall, however, Canadell et al., (2021) summarise that "thawing terrestrial permafrost will lead to carbon release (high confidence), but there is low confidence in the timing, magnitude and

relative roles of CO_2 and CH_4" of the permafrost carbon-climate feedback."). *See also* International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 31 ("Permafrost emissions today and in the future are on the same scale as large industrial countries but can be minimized if the planet remains at lower temperatures. If we limit warming to 1.5°C, emissions through 2100 will be about as large as those of India today, 2.5Gt/ year, totaling around 150Gt CO_2 by 2100. Should we instead reach 2°C, permafrost emissions will about equal those of the almost the entire European Union** today on an annual basis, 3–4Gt/year, for about 200 Gt CO_2-eq by 2100. Even higher temperatures, exceeding 3–4°C by 2100, will however likely result in up to 400Gt CO_2-eq additional carbon release from permafrost, adding the equivalent of adding another United States or China (currently 5–10Gt/year) annually to the global carbon budget through 2100.").

[53] Voigt C., Maruschak M. E., Abbott B. W., Biasi C., Elberling B., Siciliano S. D., Sonnentag O., Stewart K. J., Yan Y., & Martikainen P. J. (2020) *Nitrous oxide emissions from permafrost-affected soils*, NATURE REVIEWS EARTH & ENVIRONMENT 1:420–434, 427, 429 ("High N_2O emissions in pristine permafrost regions can be expected in areas with a sparse to absent vegetation cover, a low to intermediate C:N ratio, high C and high mineral N content (in particular, NO_3^-), in combination with relatively high temperatures and a favourable (intermediate) moisture content (Fig. 4c–f). Unvegetated permafrost peatlands or other organic-rich soils, combining all these characteristics, are, therefore, prime candidates for N_2O emissions under current climate conditions [72], as are thaw-erosional features in thermokarst-affected landscapes [25,54]. For permafrost-affected soils, even slight alterations in environmental settings, such as soil warming or enhanced N availability, can induce N_2O emissions from vegetated areas [19,95,103,107]."; "Warming enhances N mineralization [137, 138] and promotes nitrification and denitrification [16], both directly and indirectly via improved substrate availability[139]. Experimental warming of air and surface soil temperature has been shown to increase N_2O emissions in subarctic [95] and alpine peatlands [134] and alpine meadows [107] by 10–460%, and can transform even vegetated ecosystems from a sink to a source of N_2O in Arctic and alpine peatlands [95,134]. Ongoing warming of the active layer can lead to permafrost thaw across permafrost regions [12], either as a gradual, top-down permafrost thaw (active-layer deepening) or abruptly, as thawing of ice-rich permafrost creates collapse features (thermokarst)[37]."); *see also* Voigt C., Maruschak M. E., Lamprech R. E., Jackowicz-Korczyynski M., Lindgren A., Mastepanov M., Granlund L., Christensen T. R. Tahvanainen T., Martikainen P. J., & Biasi C. (2017) *Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw*, PROCEEDINGS OF THE NAT'L. ACAD. OF SCIENCES, 114(24):6238–6243, 6283 ("Here we show that N_2O emissions from subarctic peatlands increase as the permafrost thaws. In our study, the highest post thaw emissions occurred from bare peat surfaces, a typical landform in permafrost peatlands, where permafrost thaw caused a fivefold increase in emissions (0.56±0.11 vs. 2.81±0.6 mg $N_2Om^{-2}d^{-1}$). These emission rates match those from tropical forest soils, the world's largest natural terrestrial N_2O source. The presence of vegetation, known to limit N_2O emissions in tundra, did decrease (by ~90%) but did not prevent thaw-induced N_2O release, whereas waterlogged conditions suppressed the emissions.") *and* Wilkerson J., Dobosy R., Sayres D. S., Healy C., Dumas E., Baker B., & Anderson J. G. (2019) *Permafrost nitrous oxide emissions observed on a landscape scale using the airborne eddy-covariance method*, ATMOSPHERIC CHEMISTRY & PHYSICS 19:4257–4268 , 4257 ("We observed large variability of N_2O fluxes with many areas exhibiting negligible emissions. Still, the daily mean averaged over our flight campaign was 3.8 (2.2–4.7) mg N_2O m^{-2} d^{-1} with the 90 % confidence interval shown in parentheses. If these measurements are representative of the whole month, then the permafrost areas we observed emitted a total of around 0.04–0.09 g m^{-2} for August, which is comparable to what is typically assumed to be the upper limit of yearly emissions for these regions.").

[54] Lenton T. M., *et al.* (eds.) (2023) *Summary Report, in* GLOBAL TIPPING POINTS REPORT 2023, 13 ("Already, at today's 1.2°C global warming, tipping of warm-water coral reefs is likely and we cannot rule out that four other systems may pass tipping points: the ice sheets of Greenland and West Antarctica, the North Atlantics Subpolar Gyre circulation, and parts of the permafrost subject to abrupt thaw.").

[55] UNEP and FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 16 ("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)").

[56] U.S. Geological Survey (2019) *Nutrients and Eutrophication* (last accessed 19 September 2024).

[57] Schulz G., Sanders T., Voynova Y. G., Bange H. W., & Dahnke K. (2023) *Seasonal variability of nitrous oxide concentrations and emissions in a temperate estuary*, BIOGEOSCIENCES 20:3229–3247, 3229 ("We found that the estuary was a year-round source of N_2O, with the highest emissions in winter when dissolved inorganic nitrogen (DIN) loads and wind speeds are high. However, in spring and summer, N_2O saturations and emissions did not decrease alongside lower riverine nitrogen loads, suggesting that estuarine in situ N_2O production is an important source of N_2O. … The overarching control of phytoplankton growth on organic matter and, subsequently, on N_2O production highlights the fact that eutrophication and elevated agricultural nutrient input can increase N_2O emissions in estuaries.").

[58] Gong C., *et al.* (2024) *Global net climate effects of anthropogenic reactive nitrogen*, NATURE 632(8025): 557–563, 557 ("Furthermore, fertilizer application and deposition of atmospheric Nr on land and ocean can alleviate N limitation in terrestrial or marine ecosystems and facilitate carbon sequestration, thereby reducing atmospheric CO_2 concentrations14,15 and exerting a cooling effect on the atmosphere (Fig. 1).").

[59] Gong C., *et al.* (2024) *Global net climate effects of anthropogenic reactive nitrogen*, NATURE 632(8025): 557–563, 557 ("Specifically, the long-lived greenhouse gas nitrous oxide (N_2O) contributes to warming of the atmosphere8, whereas short-lived ammonium (NH_4^+) and nitrate (NO_3^-) aerosols generated from ammonia (NH_3) and nitrogen oxide (NO_x) gases can scatter solar radiation and thereby cool the atmosphere[9–11].").

[60] Gong C., *et al.* (2024) *Global net climate effects of anthropogenic reactive nitrogen*, NATURE 632(8025): 557–563, 557 ("Here we show that anthropogenic Nr causes a net negative direct radiative forcing of −0.34 [−0.20, −0.50] W m^{-2} in the year 2019 relative to the year 1850. This net cooling effect is the result of increased aerosol loading, reduced methane lifetime and increased terrestrial carbon sequestration associated with increases in anthropogenic Nr, which are not offset by the warming effects of enhanced atmospheric nitrous oxide and ozone.").

[61] UNEP & FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 93 ("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."). *See also* Gong C., *et al.* (2024) *Global net climate effects of anthropogenic reactive nitrogen*, NATURE 632(8025): 557–563, 557 ("NO_x furthermore plays a pivotal role in various atmospheric chemical reactions, regulating the lifetimes and thus mole fractions of other gases, such as the greenhouse gases methane (CH_4)[12] and ozone (O_3)[13].").

[62] Gong C., *et al.* (2024) *Global net climate effects of anthropogenic reactive nitrogen*, NATURE 632(8025): 557–563, 559 ("The enhanced NOx emissions led to a significant cooling effect through decreasing CH_4 lifetime and increasing aerosol burdens, whereas the negative direct radiative forcing of aerosols was unevenly distributed and prevalent in air-polluted regions such as Northern America, Western Europe and Eastern and Southern Asia. In response to the substantial NOx increases since pre-industrial times, present-day tropospheric O_3 was found to be enhanced across the entire simulated global grid, resulting in significant increases in global tropospheric O_3 burden from 280.1 to 325.0 Tg (Extended Data Fig. 2). This O_3 enhancement partly offsets the cooling climate effects from reduced CH_4 lifetime and increased aerosol burden considering the greenhouse gas effect of O_3.").

[63] Stavrakou T., Müller J.- F., Boersma K. F., van der A R. J., Kurokawa J., Ohara T., & Zhang Q. (2013) *Key chemical NO_x sink uncertainties and how they influence top-down emissions of nitrogen oxides*, ATMOS. CHEM. PHYS. 13(17): 9057–9082, 9067–9068 ("The daily averaged NO_x lifetimes calculated for MINLOSS and MAXLOSS cases are shown in Fig. 4 and the contribution of the main individual NO_x sinks to the total sink is illustrated in Fig. 5 for MAXLOSS. Lifetimes of less than one day are calculated in the case of MAXLOSS over most continental regions, especially in summertime and in high-NO_x environments, due to the dominance of the loss via OH. In essence, the distribution of the NO_2+OH sink reflects mainly the boundary layer OH concentration field pattern (Fig. 5). The loss

via $NO+HO_2$ occurs mostly over tropical regions, and is, on average, roughly two times lower than the loss due to NO_2+OH. In January, N_2O_5 uptake by aerosols is significant in regions with high aerosol concentrations and long nights, and is estimated to be three times more important than in July at the global scale (Fig. 5). Over oceans and high-latitude regions the lifetime can reach several days due to lower OH and NO_2 levels.").

[64] Gong C., *et al.* (2024) *Global net climate effects of anthropogenic reactive nitrogen*, NATURE 632(8025): 557–563, 562 ("Future reductions in anthropogenic Nr will likely weaken this net cooling effect mainly through a reducing atmospheric aerosol burden and an increased CH_4 lifetime, whereas the future effect of warming from fertilizer-induced N_2O emissions will remain or even increase. Our findings thus imply that to alleviate the negative environmental effects of Nr without larger rates of climate change, **stronger reductions in the emission of greenhouse gases CO_2 and CH_4 need to be implemented concurrently with Nr reductions.**").

[65] Gong C. & Zaehle S. (2024) *How nitrogen compounds in fertilizers and fossil-fuel emissions affect global warming*, Research Briefing, NATURE 632, 1–2, 2 ("In most of the future climate scenarios defined by the IPCC, emissions of nitrous oxide remain high as a result of continued agricultural fertilizer use. This implies that ambitious action will be needed to abate these emissions, weaken their warming effect and protect the stratospheric ozone layer. Furthermore, modelling of some scenarios suggest that reducing fossil-fuel-related Nr emissions will not only alleviate Nr pollution, but also diminish Nr-based cooling. This means that stronger efforts to reduce fossil-fuel-associated greenhouse-gas emissions are needed in combination with Nr reduction to achieve both environmental protection and climate-change mitigation.").

[66] UNEP and FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 89 ("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.").

[67] Nguyen D.-H., Lin C., Vu C.-T., Cheruiyot N. K., Nguyen M. K., Le T. H., Lukkhasorn W., Vo T., & Bui X.-T. (2022) *Tropospheric ozone and NOx: A review of worldwide variation and meteorological influences*, ENVTL. TECH & INNOVATION 28: 102809, 2 ("NO_x, VOCs (volatile organic compounds) together with CO (carbon monoxide) are key precursors involving the forming process of O3 (Finlayson-Pitts and Pitts, 1999). In the presence of sunlight, nitrogen dioxide (NO_2), as a surrogate for the NOx family, reacts to form ozone and nitric oxide (NO). The NO_2 is then recycled by a reaction between NO and free radicals formed from the volatile organic compounds (VOCs). VOCs were quickly noticed and reduced under the United States' ozone control effort in the 1980s (Sillman, 1993). However, the reduction of VOCs alone was insufficient to diminish O3. Thereafter, NOx control was conducted simultaneously, which resulted in a decrease in O3 levels (Burns et al., 2011). On the other hand, VOCs can only react several times before their molecules reach a short carbon chain that ceases to be photoreactive (EPA, 1999). Therefore, NOx emission control is essential in reducing tropospheric O3 concentrations (Lee et al., 2019a)"); *see also* Gong C., Kou-Giesbrecht S., & Zaehle S. (2024) *Anthropogenic-driven perturbations on nitrogen cycles and interactions with climate changes*, GREEN AND SUSTAINABLE CHEMISTRY 46:100897, 3 ("In general, increased atmospheric NOx concentrations will lead to higher OH concentrations, further increasing O_3 concentrations [14] … A recent assessment based on an ensemble of Earth System models showed that NO_x-induced O_3 enhancement warmed the climate by +0.2 $\pm$ 0.07 W m^{-2}, …").

[68] Nguyen D.-H., Lin C., Vu C.-T., Cheruiyot N. K., Nguyen M. K., Le T. H., Lukkhasorn W., Vo T., & Bui X.-T. (2022) *Tropospheric ozone and NOx: A review of worldwide variation and meteorological influences*, ENVTL. TECH & INNOVATION 28: 102809, 2 ("As one of the main environmental concerns, tropospheric O_3 causes many severe respiratory diseases in humans, e.g., pneumonia, chronic obstructive pulmonary disease, damaged lung tissues, and

respiratory mucous membranes (Tao et al., 2012; Luong et al., 2018; Farzad et al., 2021). Long-term exposure to high O_3 levels can cause significant crop yield losses (Xu, 2020; Ren, 2021; Chaudhary and Rathore, 2022).").

[69] UNEP & FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 18 ("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)"). *See also* Malley C. S., Henze D. K., Kylenstierna J. C. I., Vallack H. W., Davila Y, Anenberg S. C., Turner M. C., & Ashmore M. R. (2017) *Updated Global Estimates of Respiratory Mortality in Adults ≥ 30 Years of Age Attributable to Long-Term Ozone Exposure*, ENVTL HEALTH PERSPECTIVES 125(8):087021, 1 ("We estimated 1.04–1.23 million respiratory deaths in adults attributable to O_3 exposures using the updated relative risk estimate and exposure parameters, compared with 0.40–0.55 million respiratory deaths attributable to O_3 exposures based on the earlier CPS-II risk estimate and parameters. Increases in estimated attributable mortality were larger in northern India, southeast China, and Pakistan than in Europe, eastern United States, and northeast China.").

[70] Zhang J., Wei Y., & Fang Z. (2019) *Ozone Pollution: A Major Health Hazard Worldwide*, FRONTIERS IN IMMUNOLOGY 10:2518, 6 ("An estimated 9–23 million (8–20% of total) asthma-related emergency room visits globally were attributable to ozone (74). A large multicity study in China showed that short-term exposure to ambient ozone was associated with higher non-accidental and cardiovascular mortality (20).").

[71] Pan S.-Y., He K.-H., Lin K.-T., & Chang C.-T. (2022) *Addressing nitrogenous gases from croplands toward low-emission agriculture*, CLIMATE & ATMOSPHERIC SCI. 46:100897, 1 ("NH_3 is a prevailing atmospheric pollutant with a wide variety of adverse impacts. It can neutralize a large portion of acidic species, such as SO_x and NO_x, to form ammonium-containing aerosols. These aerosols constitute the major components of fine particulate matter ($PM_{2.5}$), which causes air quality degradation and adverse impacts on human health."); Wyer K. E., Kelleghan D. B., Blanes-Vidal V., Schauberger G., & Curran T. P. (2022), *Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health*, J. OF ENVTL. MGMT. 323:116285, 5 ("Once NH_3 is released from agricultural sources, it can then travel in a gaseous form through the atmosphere for short or long distances (Philippe et al., 2011). When NH_3 interacts with a surface, it adheres and is removed from the atmosphere (i.e. dry deposition to plant surfaces), or following chemical transformation, it is deposited remotely through rainfall (wet deposition) (Asman et al., 1998). The rate of both dry and wet deposition is dependent on a number of factors including meteorological conditions, the physical and chemical properties of the pollutant and surrounding surface conditions, and concentrations of other atmospheric pollutants (Doyle et al., 2017). Chemical reactions in the atmosphere involving NH_3 contribute significantly to the generation of $PM_{2.5}$ (Giannakis et al., 2019). Gaseous NH_3 reacts with aerosols containing sulphuric and nitric acids to create particulates such as ammonium nitrate (NH_4NO_3), ammonium sulphate ($(NH_4)_2SO_4$), and ammonium chloride (NH_4CL) (Gong et al., 2013). Bauer et al. (2016) explains how phase partitioning between inorganic aerosols is driven primarily by NH_3.").

[72] Yang H., Huang X., Westervelt D., Horowitz L., & Peng W. (2023) *Socio-demographic factors shaping the future global health burden from air pollution*, NATURE SUSTAINABILITY 6:58–68, 58 ("Exposure to ambient particulate matter (PM2.5) is a major global health threat, causing 3-9 million worldwide premature deaths every year.[1–3] The health burden is unevenly distributed across countries and disproportionally borne by the Global South. At present, more than half of PM2.5-related deaths occur in China and India, due to their heavy reliance on fossil fuels, insufficient pollution controls, as well as large size of affected population.[4,5] In fact, fossil fuel combustion alone contributes to about 4 million PM2.5-related deaths globally, and its relative contribution is higher in lower-income regions.[6]").

[73] Soil Association (2020) *Fixing Nitrogen: The challenge for climate, nature, and health*, 13 ("When there is a surplus of nitrogen, some plants and fungi do better than others. Nitrogen-tolerant species such as nettles and hemlock thrive with these high nutrient levels to the detriment of more sensitive species, reducing wildlife diversity. The impact of

excess nitrogen levels is being felt in protected habitats (such as marshes, bogs, meadows and woods) where nitrogen is not routinely applied but reaches habitats through atmospheric deposition.").

[74] Soil Association (2020) *Fixing Nitrogen: The challenge for climate, nature, and health*, 13 ("Reactive nitrogen is soluble and therefore easily makes its way into and through water systems. Increased levels of nutrients in watercourses encourage plant growth, particularly those such as algae. These 'algal blooms' reduce light and oxygen levels in water, a process known as eutrophication, which alters plant communities, kills fish and has effects all the way up the marine and freshwater food chains.").

[75] Baffes J. & Koh W. C. (11 May 2022) *Fertilizer prices expected to remain higher for longer*, World Bank Data Blog (*last visited* on 15 June 2022) ("Rising natural gas prices, especially in Europe, led to widespread production cutbacks in ammonia—an important input for nitrogen-based fertilizers. Similarly, soaring prices of coal in China, the main feedstock for ammonia production there, forced fertilizer factories to cut production, which contributed to the increase in urea prices. Higher prices of ammonia and sulfur have also driven up phosphate fertilizer prices.").

[76] ETC Group (2022) *Food Barons 2022: Crisis Profiteering, Digitalization, and Shifting Power*, 45 ("In China, the main feedstock of nitrogen production is coal as opposed to natural gas in other regions.[34] To tackle surging raw material costs and to address domestic food security concerns, China curbed its fertilizer exports in October, followed by Russia in November.[35, 36]").

[77] ETC Group (2022) *Food Barons 2022: Crisis Profiteering, Digitalization, and Shifting Power*, 45 ("The biggest buyers of China's fertilizers – India, Pakistan and other countries in Southeast Asia – felt the crunch.[37], [38] Acute shortages caused long queues,[39] protests,[40] and even deaths[41] in some Indian towns, and the government announced record subsidies to counteract exorbitant input costs.[42]").

[78] Domm P. (6 Apr 2022) *A fertilizer shortage, worsened by war in Ukraine, is driving up global food prices and scarcity*, CNBC ("Russia also exported 11% of the world's urea, and 48% of the ammonium nitrate. Russia and Ukraine together export 28% of fertilizers made from nitrogen and phosphorous, as well as potassium, according to Morgan Stanley.").

[79] Baffes J. & Koh W. C. (11 May 2022) *Fertilizer prices expected to remain higher for longer*, World Bank Data Blog (*last visited* on 15 June 2022) ("Fertilizer prices have risen nearly 30% since the start of 2022, following last year's 80% surge. Soaring prices are driven by a confluence of factors, including surging input costs, supply disruptions caused by sanctions (Belarus and Russia), and export restrictions (China). Urea prices have surpassed their 2008 peaks, while phosphates and potash prices are inching closer to 2008 levels. Concerns around fertilizer affordability and availability have been amplified by the war in Ukraine.").

[80] Houlton B.Z., *et al.* (2019) *A World of Cobenefits: Solving the Global Nitrogen Challenge*, EARTH'S FUTURE 7:865–872, 865 ("Conversely, poor management practices and inefficient nitrogen fertilizer applications to agricultural lands are harming the economy: several hundred billion US$ of annual financial losses are ascribed to excess nitrogen use in developed nations (Brink et al., 2011; Compton et al., 2011). Much of the social cost of nitrogen inefficiency is embedded in human health risks, such as cancer and upper respiratory disease (Townsend et al., 2003), in addition to accelerated nitrous oxide emissions leading to global climate change and high nitrogen loadings resulting in impaired drinking water and toxic algal blooms in downstream ecosystems (Davidson, 2009; Galloway et al., 2003).").

[81] U.S. EPA (2023) *Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*, 1, 154 ("The SCGHG is the monetary value of the net harm to society from emitting a metric ton of that GHG into the atmosphere in a given year. In principle, the SC-GHG is a comprehensive metric that includes the value of all future climate change impacts (both negative and positive), including changes in net agricultural productivity, human health effects, property damage from increased flood risk, changes in the frequency and severity of natural

disasters, disruption of energy systems, risk of conflict, environmental migration, and the value of ecosystem services."; *see* Table A.5 "Annual Unrounded SC-CO_2, SC-CH_4, and SC-N_2O Values, 2020-2080").

[82] Mandrini G., Pittelkow C. M., Archontoulis S., Kanter D., & Martin N. F. (2022) *Exploring Trade-Offs Between Profit Yield, and the Environmental Footprint of Potential Nitrogen Fertilizer Regulations in the US Midwest*, FRONTIERS IN PLANT SCIENCE 13:852116, 12 ("Welfare can be understood by the sum of after policy farmers' income (profits + compensation) and the environmental damage caused by nitrate losses (by assuming that tax, fees, and compensations are monetary transfers between the farmers and the rest of society, we can suppress them from the welfare computation). Considering that the environmental cost from groundwater contamination is 16.1 US$ per kg N (Sobota et al., 2015; Jin et al., 2019) (including undesirable odor and taste, nitrate contamination, increased colon cancer risk, and increased eutrophication), our simulated dataset suggests that reducing N fertilizer use will reduce externalities by an estimated 524 million US$/year. This represents an increase in the welfare of 377 million US$/year and a return on investment of 260%, showing how beneficial it is to reduce N loading upfront rather than handling the externalities associated with environmental pollution and human health damages.").

[83] Mandrini G., Pittelkow C. M., Archontoulis S., Kanter D., & Martin N. F. (2022) *Exploring Trade-Offs Between Profit Yield, and the Environmental Footprint of Potential Nitrogen Fertilizer Regulations in the US Midwest*, FRONTIERS IN PLANT SCIENCE 13:852116, 13 ("Similarly, the policies explored in our work could encourage more efficient N management besides the reduction in N fertilizer consumption explored here. Such synergies are possible in the ratio, leaching fee, and balance fee policies. Those policies can raise the adoption of practices and technologies that increase N use efficiency, i.e., enhanced fertilizers, split applications, cover crops, and others. For example, Sela et al. (2019) evaluated how N balance levels changed by improved timing and formulation of fertilizer applications. A larger market for efficient technologies would in turn create incentives for the private and public sectors to invest in research and launch products that help save N fertilizer inputs. It will also increase incentives for breeding organizations to focus on more N-efficient genetics. One of these practices, cover crops, has also been identified as one of the most effective "nature-based" carbon mitigation approaches (Fargione et al., 2018).").

[84] Gu B., *et al.* (2023) *Cost effective mitigation of nitrogen pollution from global croplands*, NATURE 613:77–84, 80 ("Our estimated net economic benefit to the whole of society resulting from abatement of N_r losses from croplands, considering benefits to crop yield, human health, ecosystems and climate change, are approximately 25 times that of the implementation cost, that is, 476 ± 123 billion USD (Fig. 3a and Supplementary Table 4). Yield increase alone is estimated to contribute 196 ± 45 billion USD, mainly in regions with low crop yields, such as the Middle East and North Africa and sub-Saharan Africa owing to insufficient use of N fertilizers, and in China and India owing to overuse of N fertilizers.").

[85] Jörß W., Ludig S., & Schneider L. (2023) *Mitigation potentials for emissions of nitrous oxide from chemical industry in industrialised countries world-wide*; and Patel P. (2021) *Nitrous oxide: The unnoticed greenhouse gas*, C&EN 99:20–23. ("The Global Efficiency Intelligence estimated that N_2O emissions from adipic acid manufacturing amounted to 142.5 MtCO_2e in 2021. The Nitric Acid Climate Action Group estimated that N_2O emissions from nitric acid manufacturing and caprolactam manufacturing in industrialized countries amounted 35.1 MtCO_2e and 3.4 MtCO_2e. Meanwhile, Patel (2021) reported that caprolactam facilities emitted about 35,000 t of N_2O, which is approximately 9.5 MtCO_2e. This yields an inference that total N_2O emissions from caprolactam facilities amounted to ~6.08 MtCO_2e. Adding all emission estimates from the acid and caprolactam manufacturing and then subtracting the sum from the total N_2O emissions yields a result of 2.92 MtCO_2e emitted from nitric acid manufacturing in developing countries for a total of 38.02 MtCO_2e from nitric acid manufacturing.").

[86] Hasanbeigi A. & Sibal A. (2023) *Stopping a Super-Pollutant: N_2O Emissions Abatement from Global Adipic Acid Production*, 15 (*see* Figure 7 on adipic acid value chain with the intermediary and consumer products).

[87] Hasanbeigi A. & Sibal A. (2023) *Stopping a Super-Pollutant: N_2O Emissions Abatement from Global Adipic Acid Production*, 22–23 ("The global market size for nylon 6,6 in 2021 was around 5.25 billion $/yr (Maximize market

research, 2022). The share of automotive industry from the global nylon 6,6 market in 2021 was about 3.7 billion $/yr. Therefore, the impact of required investment in N_2O abatement technologies in adipic acid plants on automotive industry (30 M$/yr) is less than 1% of the cost to purchase nylon 6,6 by the global automotive industry").

[88] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 ("Global demand for adipic aid is projected to grow 87% from 2015–2030."); *see also* Hasanbeigi A. & Sibal A. (April 2023) *Stopping a Super-Pollutant: N_2O Emissions Abatement from Global Adipic Acid Production*, 14 ("The adipic acid market is anticipated to have substantial growth in the future with the rising demand for adipic acid in the global market (Tealfeed, 2021).").

[89] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 ("Of the 21 adipic acid plants worldwide, 11 are in China, making it the largest emitter of N_2O (Table 2)."); Hasanbeigi A. & Sibal A. (2023) STOPPING A SUPER-POLLUTANT: N_2O EMISSIONS ABATEMENT FROM GLOBAL ADIPIC ACID PRODUCTION, Global Efficiency Intelligence, 2 ("There are estimated to be 39 operational facilities globally producing adipic acid while almost two thirds of the global adipic acid production takes place in China and U.S. Adipic acid production is one of the largest sources of nitrous oxide (N_2O) emissions.").

[90] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 ("Of the 21 adipic acid plants worldwide, 11 are in China, making it the largest emitter of N_2O (Table 2).").

[91] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 ("Of the two plants in the United States, one reduces over 95% of its emissions, and the other has a variable abatement history, with large increases in emissions since 2010.").

[92] Hasanbeigi A. & Sibal A. (2023) STOPPING A SUPER-POLLUTANT: N_2O EMISSIONS ABATEMENT FROM GLOBAL ADIPIC ACID PRODUCTION, Global Efficiency Intelligence, 2 ("There are estimated to be 39 operational facilities globally producing adipic acid while almost two thirds of the global adipic acid production takes place in China and U.S. Adipic acid production is one of the largest sources of nitrous oxide (N_2O) emissions.").

[93] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 (*see* Table 2 Industrial and energy sector emissions of N_2O (kt N_2Oyr^{-1}) in 2020 showing emissions from China, U.S., Republic of Korea, Japan, Brazil, Germany, France, and Italy).

[94] U.S. EPA (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 26 ("However, emissions increased by 27% between 2010 and 2015. . . The upward trend in emissions between 2010 and 2015 is primarily a result of an increase in adipic acid production without N_2O abatement in China.").

[95] McKenna P., Pike L., & Northrop K. (6 August 2020) *'Super-Pollutant' Emitted by 11 Chinese Chemical Plants Could Equal a Climate Catastrophe*, INSIDE CLIMATE NEWS ("Eleven adipic acid plants in China produce nearly half of the world's adipic acid, a chemical used to make nylon and polyurethane. Nitrous oxide emissions from the plants likely equal greenhouse gas emissions of approximately 25 million automobiles, more than all cars in California, Beijing, and Shanghai combined.").

[96] Lim J., Fernandez C. A., Lee S. W., & Hatzell M. C. (2021) *Ammonia and Nitric Acid Demands for Fertilizer Use in 2050*, ACS ENERGY LETTERS 6:3676–3685, 3676, 3681 ("The global market of nitric acid (HNO_3), while lower than ammonia, is also expanding largely due to the growth in synthetic fertilizers ";"The value of the nitric acid market is expected to grow with CAGR of 3.4% yearly in the next decade.[12] If the growth rate is preserved through 2050, the market value will increase from US$24 billion in 2019 to US$68 billion in 2050. If there is accelerated market growth, with a CAGR of 3.4% between 2020 and 2030, a CAGR of 3.9% between 2030 and 2040, and a CAGR of 4.4% between 2040 and 2050, the projected market value may reach US$78 billion in 2050. Similarly, assuming

decelerating market growth over the next few decades, with a CAGR of 3.4% between 2020 and 2030, a CAGR of 2.9% between 2030 and 2040, and a CAGR of 2.4% between 2040 and 2050 could result in a projected market value of US$58 billion in 2050 (Figure 4b).").

[97] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 ("Similarly to N_2O from adipic acid production, N_2O emissions from nitric acid production are projected to increase by 17% between 2015 and 2030 if no further abatement technology is employed, owing to the growing demand for synthetic nitrogen fertilizers and industrial explosives.").

[98] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 ("Of the approximately 580 nitric acid production plants worldwide, only about 100 abate N2O emissions. The nations with the largest emissions in 2020 were the United States, Russia, China, and Australia (Table 2).").

[99] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 ("The nations with the largest emissions in 2020 were the United States, Russia, China, and Australia (Table 2).").

[100] Patel P. (2021) *Nitrous oxide: The unnoticed greenhouse gas*, C&EN 99:20–23, 21 ("Another N_2O culprit is the production of caprolactam, a raw material for nylon 6. Globally, caprolactam facilities emit about 35,000 t of N_2O per year, equal to about 10 million t of carbon dioxide. Producing caprolactam involves oxidizing ammonia at high temperatures to make ammonium nitrite, which is then hydrogenated with sulfuric acid to give hydroxylammonium sulfate. Both the oxidation and hydrogenation steps result in N_2O as a side product, says Kris Devoldere, a chemical engineer at Lanxess.").

[101] U.S. EPA (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 26 ("As of 2016, most producers of adipic acid had implemented abatement technologies, but less progress has been made in abating emissions from nitric acid plants."); ("Firms in the nylon business have taken or are starting to take action. In contrast, the nitric acid sector has mostly failed to heed calls to reduce N_2O."); Patel P. (2021) *Nitrous oxide: The unnoticed greenhouse gas*, C&EN 99:20–23, 20 ("Firms in the nylon business have taken or are starting to take action. In contrast, the nitric acid sector has mostly failed to heed calls to reduce N_2O.").

[102] Patel P. (2021) *Nitrous oxide: The unnoticed greenhouse gas*, C&EN 99:20–23, 21 ("Even if all the world's adipic acid and caprolactam makers abated their N_2O, though, emissions from nitric acid plants would negate much of the effect.").

[103] Nabuurs G. *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers, D. & Ravindranath, N.H. (eds.), ("A recent comprehensive review confirms agriculture as the principal driver of the growing atmospheric N_2O concentration (Tian et al. 2020). The latest FAOSTAT data (FAO 2020b, 2021a) document a 25% increase in AFOLU N_2O emissions between 1990 and 2019, with the average share from agriculture remaining approximately the same (96%)."); Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2558 ("Among all anthropogenic sources, direct emissions from nitrogen additions in the agricultural sector made the largest contribution to the increase, which grew from 2.2 (1.6–2.8) Tg N yr^{-1} in 1980 to 3.9 (2.9–5.1) Tg N yr^{-1} in 2020. Indirect N2O emissions also steadily increased during the study period, from 0.9 (0.71.1) Tg N yr^{-1} in 1980 to 1.3 (0.9–1.6) Tg N yr^{-1} in 2020.").

[104] Nabuurs G. *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-35 ("Both AR5 and the SRCCL described considerable increases in global use of synthetic nitrogen fertilisers since the 1970s, which was identified to be a major driver of increasing N_2O emissions (Jia et al. 2019). The latest data document a 41% increase in global

nitrogen fertiliser use between 1990 and 2019 (FAO 2021e) corresponding with associated increased N_2O emissions (Figure 7.3)."); Tian H., *et al*. (2020) *A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks*, NATURE 586: 248–256, 249 ("Direct soil emission from fertilizer application is the major source of increases in emission from agriculture, followed by a small but notable increase in emissions from livestock manure and aquaculture.").

[105] United Nations Environmental Programme (2019) *Frontiers 2018/2019: Emerging Issues of Environmental Concern*, United Nations Environment Program, Nairobi, citing Sutton, M., *et al*. (2013) *Our Nutrient World The challenge to produce more food and energy with less pollution*, viii ("The efficiency of nutrient use is very low: considering the full chain, on average over 80% of N and 25-75% of P consumed (where not temporarily stored in agricultural soils) end up lost to the environment, wasting the energy used to prepare them, and causing pollution through emissions of the greenhouse gas nitrous oxide (N_2O) and ammonia (NH_3) to the atmosphere.").

[106] Jia G., *et al.* (2019) *Land-climate interactions, in* CLIMATE CHANGE AND LAND: AN IPCC SPECIAL REPORT, Shukla P. R., *et al.* (eds.), at 134 ("In croplands, the main driver of N_2O emissions is a lack of synchronisation between crop nitrogen demand and soil nitrogen supply, with approximately 50% of the nitrogen applied to agricultural land not taken up by the crop.").

[107] Shcherbak L., *et al*. (2014) *Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen*, PROC. NAT'L. ACAD. SCI. 111:9199–9204, 9199, 9200 ("Our results suggest a general trend of exponentially increasing N_2O emissions as N inputs increase to exceed crop needs."; "Our results show that N_2O emissions tend to grow in response to N fertilizer additions at a rate significantly greater than linear; that is, we found a positive mean ΔEF for all site-years.").

[108] Broucek J. (2017) *Nitrous oxide production from cattle and swine manure*, J. OF ANIMAL BEHAVIOUR AND BIOMETEOROLOGY 5:13–19, 13 ("N_2O is produced during several microbial processes in the nitrogen (N) cycle of terrestrial and aquatic systems. Typically, 70 % to 90 % of the N ingested by herbivores is excreted, either during grazing or via application of manure collected outside grazing periods (Schils et al 2013). Housed animals excrete as dung and urine according to Paustian et al (2004) 80 to 95 % of the N in their diet, and some proportion of this N is emitted as N_2O during collection, storage, and application. Ruminants excrete between 75 and 95 % of the N they ingest, with excess dietary N increasingly excreted in the urine, while dung N excretion remains relatively constant (Castillo et al 2000; Eckard et al 2007)").

[109] Broucek J. (2017) *Nitrous oxide production from cattle and swine manure*, J. OF ANIMAL BEHAVIOUR AND BIOMETEOROLOGY 5:13–19, 14 ("The major N_2O contributor is normally the denitrification process under anaerobic conditions, but nitrification under aerobic conditions may also contribute. Nitrification and denitrification rates are affected by numerous soil and climatic or seasonal factors (Monaghan and Barraclough 1993; Chadwick et al 2000; de Klein and Eckard 2008). The rate of formation and emission of N_2O varies through time with changes in the porosity, moisture content, temperature, amount of solids in the manure, and N or dietary protein content of the soil or manure substrate (Külling et al 2001; Kebreab et al 2006; Chianese et al 2009; Li et al 2014). Anaerobically stored solid manure emitted much more N_2O than the compost (Amon et al 1998a). Chadwick et al (2000) also reported that immediate emissions of N_2O from the beef manure was likely due to rapid nitrification of ammonium or denitrification of nitrate already in the manure.").

[110] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2559, tbl. 3 ("Global anthropogenic N_2O emissions from inland waters, estuaries, and coastal vegetation continuously increased during 1980–2020 (Fig. 9a). Although all methods revealed an overall increasing trend in emissions, process-based models show a much smaller magnitude and increase rate than the two inventories. According to meta-analysis and models, anthropogenic emissions from inland and coastal waters increased from 0.1TgNyr^{-1} in 1980 to 0.15TgNyr^{-1} in 2020. In contrast, EGDARv7.0 and FAOSTAT showed that emissions increased from 0.33 and 0.35TgNyr^{-1} in 1980 to 0.53 and 0.57TgNyr^{-1} in 2020, respectively. Emissions from N deposition on land also

continued to increase during 1980–2020 (Fig. 9b). NMIP2 and NMIP2/EDGAR v7.0 show emissions increasing from 0.6 and 0.4$TgNyr^{-1}$ in 1980 to 0.9 and 0.6 $TgNyr^{-1}$ in 2020, respectively.").

[111] Rivera J. E. & Chara J. (2021) *CH_4 and N_2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems,* FRONTIERS IN SUSTAINABLE FOOD SYSTEMS 5: 657936*,* 4, 5 ("The production of CH_4 occurs *via* the microbial degradation of the proteins, organic acids, carbohydrates, and soluble lipids present in excreta (Khan et al., 1997). According to the IPCC-Tier 1 (2006), 1 kg of CH_4 is emitted from dung annually per adult head of cattle in grazing systems, but according to others reports these values may be lower (0.45–0.67 kg/animal/day), and can be highly variable (IPCC (Intergovernmental Panel on Climate Change)., 2019)."; "While most of CH_4 emissions from manure occur during storage under anaerobic conditions, in tropical regions manure can also be a generator of a considerable amount of emissions of this gas at the grassland level (Montes et al., 2013; Cai et al., 2017)."; "Organic matter is the main input for triggering methane production processes. The increase of available organic matter, and its subsequent decomposition in soils under anaerobic conditions, stimulates methanogenesis by providing a substrate for the production of acetate and hydrogen and causing soil reducing conditions (Sass et al., 1991).").

[112] Dalby F. R., Hafner S. D., Petersen S. O., Van der Zaag A. C., Habewold J., Dunfield K., Chantigny M. H., & Sommer S. G. (2021) *Understanding methane emission from stored animal manure: A review to guide model development*, J of Envtl. Quality 50(4):817–835, 818 ("Global estimates suggest that livestock manure contributes about 6% of total anthropogenic CH_4 emissions (Yusuf et al., 2012).").

[113] Wyer K. E., Kelleghan D. B., Blanes-Vidal V., Schauberger G., & Curran T. P. (2022), *Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health*, J. OF ENVTL. MGMT. 323:116285, 3–4 ("Agriculture is considered as the dominant source of atmospheric ammonia, contributing to over 81% of global NH_3 Damme et al., 2021). The primary sources of NH_3 emissions (Van emissions from agriculture include livestock and animal production, manure handling and storage, livestock housing and the application of manure/slurry and artificial fertilizers to land (Behera et al., 2013; Mikkelsen et al., 2011; Sutton et al., 2013) (Fig. 2)."; "Excreta from livestock, including uric acid, urea and faeces, can be decomposed or volatilized to form NH_3 (Behera et al., 2013). There are several microbiological processes involved in the degradation of these compounds to NH_3. Uric acid in the presence of oxygen (O_2) and water (H_2O) is converted to carbon dioxide (CO_2) and NH_3 by the enzyme uricase (equation (1a)). Urea is degraded to CO_2 and NH_3 by the enzyme urease, which is produced by various microbes often present in manure (equation (1b)). Undigested proteins present in manure are converted to NH_3 by both the enzymes uricase and urease, as well as the action of bacterial metabolism (equation (1c)).").

[114] U.S. EPA Center for Corporate Climate Leadership (2023) *Greenhouse Gas Inventory Guidance: Direct Emissions from Mobile Combustion Source*, 2 ("The greenhouse gases CO_2, CH_4, and N_2O are emitted during the combustion of fuels in mobile sources. For on-road vehicles less than 20 years old, CH_4, and N_2O emissions typically account for less than one percent of total GHG emissions. However, for older on-road vehicles, and for non-road or alternative fuel vehicles (such as a bus or trash truck using compressed natural gas), CH_4, and N_2O could be five percent or more of total GHG emissions.").

[115] Colorado A., McDonell V., & Samuelsen S. (2017) *Direct emissions of nitrous oxide from combustion of gaseous fuels*, J. OF HYDROGEN ENERGY 42(1):711–719, 711–712 ("A variety of gaseous fuel mixtures without fuel nitrogen including natural gas were considered, including, biogas and natural gas with up to 70% H_2 added (by volume). The results indicate that combustion of these fuels can directly emit significant levels of N_2O, in particular during transient events such as ignition and blowoff. Furthermore, steady state combustion of hydrogen enriched natural gas flames (which can be operated at very lean conditions due to the stabilizing effects of hydrogen), can also lead to the direct emissions of N_2O. … Relative to the consideration of N_2O emissions from combustion of fuels, most of the research in the combustion literature focuses on N_2O emissions from solid and liquid fuels, since these fuels contain nitrogen bonded within their molecular structures (fuel-nitrogen), which can be oxidized into N_2O under relatively low temperature conditions [8], [9], [10]. Significant N_2O emissions (>25 ppmdv) have been observed from coal and oil

burning power plants, but not from industrial gas flames, even when doped with an equivalent amount of fuel nitrogen [11]. As a result, the literature survey focuses on N_2O emissions from coal fired combustion [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18]. In particular, fluidized bed coal combustion has been identified as a specific technology that can emit significant amounts of N_2O ($25 < N_2O < 85$ ppmdv).").

[116] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 599 (*see* Table 2 stating that "[f]lue gas concentration are low; hence options are limited. Catalytic and non-catalytic reduction techniques are more efficient for NO_x and may even trigger some N_2O formation.").

[117] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 599 (*see* Table 2 stating that "[s]witching fuels from coal and oil to natural gas and to renewable would substantially reduce emissions from these sectors.").

[118] Van Wijnen J., *et al.* (2015) *Future Scenarios for N_2O Emissions from Biodiesel Production in Europe*, J. INT. ENVIRON. SCI. 12:17–30, 18 ("For growing first generation energy crops a considerable amount of synthetic fertiliser and fossil energy is needed and also the biofuel production processes require additional fossil energy. These inputs give rise to GHG emissions additional to the emissions caused by the combustion of the biofuel itself, making the use of biofuels less favourable to combat GHG emissions, as demonstrated in studies on the life cycle of biofuels from energy crops. A major concern is the use of synthetic nitrogen containing fertilisers (N-fertilisers), because these could be partly converted into nitrous oxide (N_2O), which has a large Global Warming Potential (GWP), about 296 times larger than CO_2."); Nabuurs G. *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-35 ("Increased fertiliser use has been driven by pursuit of increased crop yields, with for example, a 61% increase in average global cereal yield per hectare observed during the same period (FAO 2021c), achieved through both increased fertiliser use and varietal improvements. Increased yields are in response to increased demand for food, feed, fuel and fibre crops which in turn has been driven by a growing human population (FAO, 2019), increased demand for animal-sourced food and bioenergy policy (OECD/FAO 2019).").

[119] Van Wijnen J., *et al.* (2015) *Future Scenarios for N_2O Emissions from Biodiesel Production in Europe*, J. INT. ENVIRON. SCI. 12:17–30, 22 ("We calculated the amount of N_2O emitted as a result of cultivation of energy crops in our future scenarios (S1–S3) and the increase of N_2O emissions relative to the baseline scenario (S0). In all three scenarios the total N_2O emission from synthetic fertiliser use in Europe increased by 43–86 Gg/y (24–45%) compared with the 178 Gg N_2O/y in the baseline scenario. In the baseline scenario S0, the N_2O emissions increased by 20 Gg N_2O/y (13%) between 2000 and 2050 as a result of increased fertiliser use in the GO2050 scenario. This implies that in our alternative scenarios (S1–S3) the N_2O emissions increase by 63–106 Gg/y (40–67%) relative to 2000.").

[120] Garcia C. A., *et al.* (2011) *Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico*, APPLIED ENERGY 88:2088–2097, 2096 ("It was necessary to include an ethanol transportation phase in the Brazilian case to have consistent system boundaries with Mexico. Ethanol emissions in Brazil are 26.6 kgCO_2e/GJ ethanol without considering transportation to admixture plants. When transportation similar to that of Mexico is included, the ethanol emissions increase to 27.5 kgCO_2e/Gjethanol. None of the modalities analyzed in Mexico achieve higher mitigation than the Brazilian case. The emission value for the reference fossil fuel was taken from because reliable values for life cycle emissions of gasoline in Mexico do not exist at present. GHG emissions are higher because of LUC when sugarcane cultivation expands to new growing areas. This increase in GHG emissions is especially important when rainforest is converted to sugarcane crops. Under this hypothesis, all modalities generate emissions between 47% and 267% above the fossil reference. However, Johnson estimates that it is possible to expand sugarcane cultivation on 2.9 million hectares of actual grasslands, both native and cultivated. GHG emissions are much lower when sugarcane expansions occur on grasslands, such as in the EMB, EDJ, and EDJE modalities (Fig. 3)."). *See also* Hassan M. N. A., Jaramillo P., & Griffin W. M. (2011) *Life cycle GHG emissions from Malaysian oil palm bioenergy development: The impact on transportation sector's energy security*, ENERGY POL'Y 39:2615–2625,

2615 ("When converting primary and secondary forests to oil-palm plantations between 270–530 and 120–190 g CO_2-equivalent per MJ of biodiesel produced, respectively, is released."); and Valin H., *et al.* (2015) *The land use change impact of biofuels consumed in the EU Quantification of area and greenhouse gas impacts*, at x–xi ("1 Conventional biodiesel feedstocks have high LUC effects compared to the direct emissions resulting from the biofuel production process, with very high emissions for palm oil (231 grams of CO_2e per megajoule of biofuel consumed – gCO_2e/MJ), high emissions for soybean oil (150 gCO_2e/MJ) and 63 and 65 gCO_2e/MJ for sunflower and rapeseed respectively; 2 Drainage of peatlands in Indonesia and Malaysia plays a large role in LUC emissions for vegetable oils. This is especially the case for palm oil: 69% of gross LUC emissions for palm oil is caused by such peatland oxidation after land conversion; 3 The large and local emission source of peatland oxidation has an impact on the LUC values of other vegetable oils through the substitution effect, with vegetable oils interchangeable to a certain extent. Based on empirical data, we conjecture a relatively limited substitution effect, hence the large difference in LUC values for palm oil – the most cost competitive vegetable oil – and other more costly vegetable oils. Still, substitution plays a role and transfers some of the peatland emissions from palm oil to other vegetable oils; 4 The conventional ethanol feedstocks – sugar and starch – have much lower LUC emission impacts, at 14 and 34 gCO_2e/MJ biofuel consumed for maize and wheat, 17 gCO_2e/Mj for sugarcane and 15 gCO_2e/MJ for sugarbeet. These feedstocks lead to a much lesser extent to peatland oxidation and deforestation compared to vegetable oils;").

[121] Jeswani H. K., Chilvers A., & Azapagic A. (2020) *Environmental sustainability of biofuel: a review*, PROC. ROYAL SOC. A, 476:1–37, 12 ("On the other hand, harvesting of agricultural and forest residues can result in reduction of the land carbon stock, thus increasing GHG emissions; however, most of the studies did not account for these changes. In the case of bioethanol from agricultural residues, other factors, such as the consideration of agricultural emissions, pre-treatment methods and source of energy for the biorefinery, have a significant influence on GHG emissions.").

[122] Fajardy M., Koberle A., Mac Dowell N., & Fantuzzi A. (2019) *BECCS deployment: a reality check*, Grantham Institute Briefing Paper No. 28, 3 ("BECCS requires significant inputs of land, nitrogen, phosphorus and water, with substantial CO_2 and nitrous oxide emissions arising from these inputs. [7] It also raises the prospect that BECCS 'may largely transfer environmental risk from the atmosphere to the land'.[9]"); Muri H. (2018) *The role of large-scale BECCS in the pursuit of the 1.5°C target: an Earth system model perspective*, ENVTL. RES. LETTERS 13:044010, 2 ("Fertilizer use in growing biocrop cultivation is another concern that should be taken into account when considering the total impacts of BECCS. Nitrous oxide is a bi-product of nitrogen fertilizer use, with a global warming effect of 296 times that of CO2 (Crutzen et al. 2008). Poppet et al. (2014) and Kato and Yamagata (2014) estimate emissions from fertilizing biocrops to be of 3–24GtCO_2-equivalent and 5.1 Pg C-equivalent (18.7 GtCO_2-equivalent), respectively, during the 21st century for ∼2◦Cglobal warming scenarios. Fertilizer availability may prove to become a constraint, as well as water scarcity. Biocrop production requires energy inputs for machinery used for soil preparation and seed sowing, cultivation, irrigation infrastructure, harvest, and transportation to the processing plant (Qin et al 2006). Fertilizer, pesticides, and herbicides may result in additional carbon costs through its manufacture, transportation and application procedure.").

[123] Bertagni M. B., Socolow R. H., Martinez J. M. P., Carter E. A., Greig C., Ju Y., Lieuwen T., Mueller M. E., Sundaresan S., Wang R., Zondlo M. A., & Porporato A. (2023) *Minimizing the impacts of the ammonia economy on the nitrogen cycle and climate*, PNAS 120(46): e2311728120, 1 ("Several low-carbon energy carriers are being explored as alternatives to fossil fuels to limit global warming. Among these, hydrogen (H_2) has the largest potential to be the low-carbon fuel of the future due to the scalability of its production (1). Hydrogen can be obtained from different energy sources (fossil fuels, biomass, renewables, nuclear, etc.) through various technologies (reforming, gasification, pyrolysis, electrolysis, etc.). Using carbon capture and storage offers a path to decarbonize hydrogen production from fossil fuels. Stoichiometrically, hydrogen combustion produces only water as a byproduct, providing an opportunity to reduce CO_2 emissions and air pollution (2). As a result of this potential, countries accounting for around 90% of the world's energy supply and use have projects for large-scale H_2 production (1, 3)… Arguably the one most actively considered by the industry is transporting ammonia after converting hydrogen through the Haber–Bosch process ($N_2 + 3 H_2 \longrightarrow 2 NH_3$) (5, 11). The energy required for the conversion would add only a small premium (~10%) on hydrogen production (11). Ammonia can be stored at much more reasonable conditions, e.g., as a liquid at

−33 °C and standard pressure or at 10 bar and room temperature. A further advantage is that the ammonia transport and storage infrastructures have matured during the last century to deliver ammonia in agriculture and industry.").

[124] Bertagni M. B., Socolow R. H., Martinez J. M. P., Carter E. A., Greig C., Ju Y., Lieuwen T., Mueller M. E., Sundaresan S., Wang R., Zondlo M. A., & Porporato A. (2023) *Minimizing the impacts of the ammonia economy on the nitrogen cycle and climate*, PNAS 120(46): e2311728120, 2–3 ("[M]ost of the nitrogen in ammonia is converted back to atmospheric N_2 during ammonia combustion ($4\ NH_3 + 3\ O_2 \longrightarrow 2\ N_2 + 6\ H_2O$) or cracking ($2\ NH_3 \longrightarrow N_2 + 3\ H_2$), thus forming a closed cycle for nitrogen and significantly reducing environmental concerns. Practically, however, leakages across the ammonia value chain and undesired reactions during ammonia use would keep the nitrogen cycle partially open, releasing reactive nitrogen compounds (e.g., NH_3, NO_x, N_2O, HONO) into the environment (Fig. 1).").

[125] Bertagni M. B., Socolow R. H., Martinez J. M. P., Carter E. A., Greig C., Ju Y., Lieuwen T., Mueller M. E., Sundaresan S., Wang R., Zondlo M. A., & Porporato A. (2023) *Minimizing the impacts of the ammonia economy on the nitrogen cycle and climate*, PNAS 120(46): e2311728120, 3 ("Accounting for leakages and combustion emissions, between ~0.5 and 5% of the nitrogen drawn from the atmosphere for ammonia production could be lost to the environment as reactive nitrogen.").

[126] Bertagni M. B., Socolow R. H., Martinez J. M. P., Carter E. A., Greig C., Ju Y., Lieuwen T., Mueller M. E., Sundaresan S., Wang R., Zondlo M. A., & Porporato A. (2023) *Minimizing the impacts of the ammonia economy on the nitrogen cycle and climate*, PNAS 120(46): e2311728120, 3 ("With an ammonia production of 1,600 Mt NH3/y, roughly equivalent to 1,300 Mt N/y, this loss rate would perturb the global nitrogen cycle by 6.5 to 65 Mt N/y (Fig. 2A). The upper bound is very large, about half of the current global perturbation due to fertilizers. At the country or regional level, even a small penetration (e.g., 5%) of ammonia in the energy market could lead to reactive nitrogen emissions that are comparable to the current cumulative emissions from agriculture, industry, and energy sectors (Fig. 2B). In addition to air pollution (27–29), these emissions would also lead to water pollution after deposition, regional alterations of ecosystems (17, 18, 30), and global warming and stratospheric ozone depletion via nitrous oxide (31).").

[127] Bertagni M. B., Socolow R. H., Martinez J. M. P., Carter E. A., Greig C., Ju Y., Lieuwen T., Mueller M. E., Sundaresan S., Wang R., Zondlo M. A., & Porporato A. (2023) *Minimizing the impacts of the ammonia economy on the nitrogen cycle and climate*, PNAS 120(46): e2311728120, 3 ("With a 1% nitrogen conversion into N_2O, an ammonia economy of 1,600 Mt NH_3/y would result in 20 Mt N_2O/y, around three times current anthropogenic emissions (31).").

[128] Law Y., Ye L., Pan Y. & Yuan Z. (2012) *Nitrous oxide emissions from wastewater treatment processes*, PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B 367:1265–1277, 1265 ("N_2O is mainly released during biological nitrogen removal in biological nutrient removal (BNR) plants. There are various configurations of BNR plants that can achieve high levels of nitrogen removal from wastewater by promoting nitrification and denitrification in different reaction zones. N_2O is a known obligatory intermediate in the heterotrophic denitrification pathway and is also produced by autotrophic nitrifying bacteria, mainly ammonia-oxidizing bacteria (AOB) [6], as a by-product.")

[129] Maktabifard M., Al-Hazmi H. E., Szulc P., Mousavizadegan M., Xu X., Zaborowska E., Li X., & Makinia J. (2023) *Net-zero carbon condition in wastewater treatment plants: A systematic review of mitigation strategies and challenges*, RENEWABLE AND SUSTAINABLE ENERGY REVIEWS 185:113638, 9 ("N_2O mitigation strategies are mainly focused on [83]: (i) Optimizing aeration mode and DO set-point, (ii) Preventing DO gradients via mixing optimization, (iii) Avoiding NH_4^+ peaks, (iv) Preventing NO_2 accumulation, (v) Ensuring complete denitrification by supplying sufficient carbon source or/and increasing hydrolysis in the primary clarifiers.").

[130] Maktabifard M., Al-Hazmi H. E., Szulc P., Mousavizadegan M., Xu X., Zaborowska E., Li X., & Makinia J. (2023) *Net-zero carbon condition in wastewater treatment plants: A systematic review of mitigation strategies and challenges*, RENEWABLE AND SUSTAINABLE ENERGY REVIEWS 185:113638, 15 ("Both direct (fugitive, process-related) and indirect (due to energy and chemicals consumption, transportation) GHG emissions have some potential for reduction.

However, implementing mitigation strategies for the net-zero carbon concept in WWTPs comes with recognized limitations and trade-offs. Effluent quality, operational cost and GHG emissions are potentially conflicting objectives [95,97,191].").

[131] Vasilaki V., Massara T. M., Stanchev P., Fatone F., & Katsou E. (2019) *A decade of nitrous oxide (N_2O) monitoring in full-scale wastewater treatment processes: A critical review*, WATER RES. 161:392–412, 407 ("However, the suggested mitigation schemes have not yet reached commercial applications at full-scale wastewater treatment processes. There is a gap between the identification of appropriate N_2O mitigation measures and their integration into the control of WWTPs. Future studies shall focus on the development, implementation and integration of the mitigation strategies into the existing control strategy of wastewater treatment processes. Special attention must be paid to trade-offs between GHG emissions, energy consumption, system performance and compliance with the legislative requirements in order to support evidence-based multi-objective optimisation of the WWTPs operation.").

[132] Winiwarter W., *et al*. (2018) *Technical Opportunities to Reduce Global Anthropogenic Emissions of Nitrous Oxide*, ENVIRON. RES. LETT. 13:1–12, 3, tbl. 1 (providing an overview of N_2O emission abatement technology implemented in GAINS). *See also* Hassan M., *et al.* (2022) *Management Strategies to Mitigate N2O Emissions in Agriculture,* LIFE 12(3), 439 ("The relationships between N2O occurrence and factors regulating it are an important premise for devising mitigation strategies. Here, we evaluated various options in the literature and found that N2O emissions can be effectively reduced by intervening on time and through the method of N supply (30–40%, with peaks up to 80%), tillage and irrigation practices (both in non-univocal way), use of amendments, such as biochar and lime (up to 80%), use of slow-release fertilizers and/or nitrification inhibitors (up to 50%), plant treatment with arbuscular mycorrhizal fungi (up to 75%), appropriate crop rotations and schemes (up to 50%), and integrated nutrient management (in a non-univocal way).").

[133] Harmsen J. H. M., van Vuuren D. P., Nayak D. R., Hof A. F., Höglund-Isaksson L., Lucas P. L., Nielsen J. B., Smith P., & Stehfest E. (2019) *Long-Term Marginal Abatement Cost Curves of Non-CO_2 Greenhouse Gases*, ENVTL. SCIENCE & POL'Y 99:136–149, 145 tbl. 2 (Total N_2O abatement potential in 2050 is 1.67 $GtCO_2e$ (AR4 GWP_{100}), with approximately 36% (0.6 $GtCO_2e$) from industrial sources (adipic and nitric acid production), 27% (0.45 $GtCO_2e$) from fertilizer use, and 30% (0.49 $GtCO_2e$) from animal waste/manure.). The CO_2e abatement potential in the *Primer* is converted into terms of AR6 GWP_{100}, rather than AR4.

[134] Harmsen J. H. M., van Vuuren D. P., Nayak D. R., Hof A. F., Höglund-Isaksson L., Lucas P. L., Nielsen J. B., Smith P., & Stehfest E. (2019) *Long-Term Marginal Abatement Cost Curves of Non-CO_2 Greenhouse Gases*, ENVTL. SCIENCE & POL'Y 99:136–149, 145 tbl. 2 (Total N_2O abatement potential in 2050 is 1.67 $GtCO_2e$ (AR4 GWP_{100}), with approximately 36% (0.6 $GtCO_2e$) from industrial sources (adipic and nitric acid production), 27% (0.45 $GtCO_2e$) from fertilizer use, and 30% (0.49 $GtCO_2e$) from animal waste/manure.).

[135] UNEP & FAO (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 16 ("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)").

[136] Dreyfus G. B., Xu Y., Shindell D. T., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA 119:e2123536119, 5 ("Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03°C in the mid-2030s and no net avoided warming until the mid-2040s due to the reduction in coemitted cooling aerosols (Fig. 3A). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith (43), but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (SI Appendix, Table S5).").

[137] Dreyfus G. B., Xu Y., Shindell D. T., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA 119:e2123536119, 5 ("In contrast, pairing decarbonization with mitigation measures targeting CH4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1 and Fig. 3B), similar to the 0.2°C to 0.25°C per decade warming prior to 2020 (38, 53). Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events (54, 55).").

[138] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040[.] … In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. **There are similar reductions of non-**CO_2 **emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%].**")(emphasis added).

[139] U.S. EPA (2012) GLOBAL ANTHROPOGENIC NON-CO_2 GREENHOUSE GAS EMISSIONS: 1990– 2030, 41 ("Between 1990 and 2005, N_2O emissions from production of nitric and adipic acid has decreased 37 percent, from 200 $MtCO_2e$ to 126 $MtCO_2e$ (see Table 4-2). Over this time period, production of nitric and adipic acid has increased. The decline in historical emissions is mostly due to widespread installation of abatement technologies in the adipic acid industry (Reimer et al, 1999). Most production capacity in these industries has been located in the OECD, but the proportion of emissions in the OECD has declined. In 1990, the OECD accounted for 83 percent of global N_2O emissions from this source, whereas the OECD is estimated to account for 68 percent of global emissions in 2005.").

[140] U.S. EPA (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 26 ("N_2O emissions from nitric and adipic acid production decreased by 28% between 1990 and 2010. . . Over the entire historical period, the production of both acids increased. Despite the production increase, emissions have historically declined due to worldwide installation of abatement technologies in the adipic acid industry.").

[141] Hasanbeigi A. & Sibal A. (April 2023) *Stopping a Super-Pollutant: N_2O Emissions Abatement from Global Adipic Acid Production*, 10, 11 ("Advanced scenario: Assumes facilities without N2O abatement technology will start to implement the single abatement technology in 2022 and all facilities will have single abatement technology installed and operating by 2030. Facilities that already have single abatement technology will start to implement dual abatement technology gradually from 2030 and all those facilities will have dual abatement technology installed and operating by 2040."; "By application of the single and dual abatement technologies globally, the annual N_2O emissions will decrease by 90% and 94% up to 2035 and 2050, respectively under the Advanced scenario. The total annual N_2O emissions of the global adipic acid industry in this scenario will drop from 142 Mt CO_2eq/yr in 2022 to 14 Mt CO_2eq/yr in 2035 and 8.1 Mt CO_2eq/yr in 2050 under the Advanced scenario.").

[142] Jörß W., Ludig S., & Schneider, L. (2023) *Mitigation potentials for emissions of nitrous oxide from chemical industry in industrialised countries world-wide*, 80, 81 ("Such low-hanging fruit N_2O mitigation potentials in nitric acid production of industrialised countries sum up to 63 % of total N_2O emissions from nitric acid production estimated for 2020 (22.5 Mt CO_2e mitigation potential out of 36.1 Mt CO_2e 2020 emissions)"; *see also* Table 45 providing a cross-country overview of nitric acid production.).

[143] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 599 ("Two main technologies for abating emissions from adipic and nitric production are thermal destruction composition and catalytic decomposition (Table 1). Both convert N_2O to dinitrogen (N_2) and oxygen, with abatement efficiency as high as 99%, although 90–95% efficiency is more typical.").

[144] U.S. EPA (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 29 ("China and the United States can reach 61% and 49% of their national abatement potential at break-even prices below \$10/tCO_2e.").

[145] Cui X., *et al.* (2021) *Global mapping of crop-specific emission factors highlights hotspots of nitrous oxide mitigation*, NATURE FOOD, 5 (*see* Table 1 on global direct N_2O emissions and mitigation potentials in croplands, ranked by mitigation potential)

[146] Cui X., *et al.* (2021) *Global mapping of crop-specific emission factors highlights hotspots of nitrous oxide mitigation*, NATURE FOOD, 5 ("Combining spatially explicit EFs with N input reduction data allows us to refine N_2O mitigation potential in global cropland. To do so, we developed gridded maps of decreased N input by capping N surplus at a level that maintains crop yield and stays within the proposed planetary boundary… Global mitigation potential from cropland N reduction was then estimated as 0.30 (0.23–1.44) TgN_2O-Nyr^{-1} , which accounted for 30% (17–53%) of global direct emissions of N_2O from cropland and was equivalent to the sum of direct soil emissions from China and the United States combined (Table 1).").

[147] Cui X., *et al.* (2021) *Global mapping of crop-specific emission factors highlights hotspots of nitrous oxide mitigation*, NATURE FOOD, 5 (*see* Table 1 on global direct N_2O emissions and mitigation potentials in croplands, ranked by mitigation potential).

[148] Amon B., van Zanten H. H. E., Sanz-Cobeña A., Marques-dos-Santos C., Corrado S., Caldeira C., Leip A., & Hutchings N. J. (2023) *Chapter 4. The scope to improve nitrogen use efficiency of European food systems*, in APPETITE FOR CHANGE: FOOD SYSTEM OPTIONS FOR NITROGEN, ENVIRONMENT & HEALTH, Leip A., Wollgast J., Kugelberg S., Costa Leite J., Maas R. J. M., Mason K. E., & Sutton M. A. (eds.), 50 ("At farm level, there is scope for significant improvement in nitrogen use efficiency (NUE) using available technologies. Values of farm-level NUE of up to 92% for arable systems, 80% for granivores, 61% for ruminant meat production, and 55% for dairy production can be achieved. Future food systems require optimized NUE through conventional and precision on-farm technologies, a close link between crop and livestock production, a reduction in food waste and improved used of by-products.").

[149] Leip A., Alessandrini R., Hutchings N. J., & van Grinsven J. M. (2023) *Chapter 1: Nitrogen and food systems*, in APPETITE FOR CHANGE: FOOD SYSTEM OPTIONS FOR NITROGEN, ENVIRONMENT & HEALTH, Leip A., Wollgast J., Kugelberg S., Costa Leite J., Maas R. J. M., Mason K. E., & Sutton M. A. (eds.), 18 ("This increases the risk of losses to the environment. The utilization of added N is incomplete, with the nitrogen use efficiency (NUE, here defined as the nitrogen reaching the product as a percentage of the nitrogen input) tending to decrease with increasing N inputs per hectare (cf. Leip et al., 2019).").

[150] Nabuurs G., *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 794 ("Sub-Saharan Africa has one of the lowest global fertiliser consumption rates, with increased fertiliser use suggested as necessary to meet projected future food requirements (Mueller et al. 2012; ten Berge et al. 2019; Adam et al. 2020; Falconnier et al. 2020).").

[151] Gao Y. & Serrenho A. C. (2023) *Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions*, NATURE FOOD 4:170–178, 173 ("By increasing the global efficiency of nitrogen use from current 42% to 67% by 2050, the total nitrogen demand could be reduced by 48% N in 2050.").

[152] Gao Y. & Serrenho A. C. (2023) *Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions*, NATURE FOOD 4:170–178, 173 ("A combination of several approaches is needed to achieve the proposed nitrogen use efficiency. This includes proper irrigation, adopting improved plant breeding of crops which utilise nitrogen fertilisers more efficiently and applying the right fertilisers at the right rate 208 and time in the right place.").

[153] Grados D., Butterbach-Bahl K., van Groenigen K. J., Olesen J. E., van Groenigen J. W., & Abalos D. (2022) *Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems*, ENVTL. RES. LETTERS 17:114024, 6 ("Considerable N_2O reductions were found for biochar amendment (−26.6%), optimization of fertilizer rate (−31.2%), slow- or controlled release fertilizer (−33.0%), nitrification inhibitors (−44.1%), urease inhibitors (−22.5%), combined use of nitrification and urease inhibitors (−49.4%), and drip irrigation (−26.5%)."); *see also* Gao Y. & Serrenho A.C. (2023) *Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions*, NATURE FOOD 4:170–178, 172, fig. 2(a) ("In total, direct and indirect N_2O emissions in the cropland account for 48% of the total emissions of synthetic nitrogen fertilisers (Fig. 1). These are generated by bacteria, and they could be reduced by the use of nitrification inhibitors. These are chemicals that can be deployed along fertilisers to prevent bacteria from performing nitrification and denitrification reactions. Urease inhibitors can also be deployed to urea to prevent its decomposition into ammonia and subsequently to N_2O. It was reported that the use of nitrification inhibitors also decreases the level of acidification of the soil. For this reason, the use of nitrification inhibitors reduces the requirements for limestone to correct acidification, consequently reducing the total CO_2 emissions. The maximum mitigation potential of using nitrification and urease inhibitors is explored in our nitrification inhibitors scenario in Fig. 2a.").

[154] Grados D., Butterbach-Bahl K., van Groenigen K. J., Olesen J. E., van Groenigen, J. W., & Abalos D. (2022) *Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems*, ENVTL. RES. LETTERS 17:114024, 6 ("As opposed to the technology-driven options, agroecological practices tended to increase N_2O emissions (figure 2). Examples of these practices are the use of organic fertilizer, diversifying crop rotations, reduced/no-tillage, and the use of cover crops. Despite the potential adverse impact on N_2O, these practices (not primarily conceived to abate N_2O emissions) are linked to a wide range of beneficial effects, including enhanced soil biodiversity (Liu et al 2016, Venter et al 2016, Chen et al 2020, Kim et al 2020), lower weed infestation (Osipitan et al 2019), increased nutrient retention (McDaniel et al 2014, Chen et al 2018, Wei et al 2021), reduced water pollution (Thapa et al 2018), reduced soil erosion (Sun et al 2015), and other ecosystem services (Iverson et al 2014, Lichtenberg et al 2017).").

[155] Nair V. D., *et al.* (2017) *Biochar in the Agroecosystem-Climate-Change-Sustainability Nexus*, FRONTIERS IN PLANT SCIENCE 8:1–9, 2 ("The International Biochar Initiative (IBI) describes biochar as "a solid material obtained from the carbonisation of biomass" (http:// www.biochar-international.org/) which occurs when biomass (such as wood, manure, or crop residues) is heated in a closed container with little or no air (Lehmann and Joseph, 2009).").

[156] Nabuurs G., *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-63 ("Biochar application to paddy rice has resulted in substantial reductions (20-40% on average) in N_2O (Awad et al. 2018; Liu et al. 2018; Song et al. 2016) (Section 7.4.3.5) and smaller reduction in CH_4 emissions (Kammann et al. 30 2017; Kim et al. 2017a; Song et al. 2016; He et al. 2017; Awad et al. 2018). Potential co-benefits include yield increases particularly in sandy and acidic soils with low cation exchange capacity (Woolf et al. 2016; Jeffery et al. 2017); increased soil water-holding capacity (Omondi et al. 2016), nitrogen use efficiency (Liu et al. 2019; Borchard et al. 2019), biological nitrogen fixation (Van Zwieten et al. 2015); adsorption of organic pollutants and heavy metals (e.g. Silvani et al. 2019); odour reduction from manure handling (e.g. Hwang et al. 2018) and managing forest fuel loads (Puettmann et al. 2020).").

[157] Guenet B., *et al.* (2021) *Can N_2O emissions offset the benefits from soil organic carbon storage?* GLOBAL CHANGE BIOLOGY 27:237–256, 246 ("The efficiency of biochar for C sequestration is twofold as compared to simply relying on soil stabilization processes. First, slow pyrolysis for biochar production results in a much higher proportion of the feedstock C bound in persistent molecular structures than through in situ stabilization by addition of unprocessed

organic matter to soil (Lehmann et al., 2006). With a slow pyrolysis at about 500°C, approximately 50% of the carbon contained in a feedstock of Miscanthus or maize cobs ended up within the biochar and can therefore be assumed to be more stable than carbon in the raw biomass (Budai et al., 2014). This compares with only 8%–12% of straw residue returned to the field being transformed into longer-lived SOM forms (Bolinder et al., 1999; Fujisaki et al., 2018). Thus, pyrolysis is about four times more efficient than SOM-formation processes to produce persistent C in soils. Second, field studies show that biochar has a longer mean residence time in soils than SOM, that is, >100 years (Rasse et al., 2017) versus about 50 years for the latter (Schmidt et al., 2011).").

[158] Lin F., Wang H, Shaghaleh H., Hamad A. A. A., Zhang Y., Yang B., & Hamoud Y.A. (2024) *Effects of Biochar Amendment on N_2O Emissions from Soils with Different pH Levels*, ATMOSPHERE 15(68): 1 ("Our results showed that adding biochar significantly decreased N_2O emissions by 20.8% and 47.6% in acidic vegetable soil for both N and no N addition treatments, respectively. For neutral and alkaline soils, the reduction of N_2O emissions by biochar amendment was only significant for N addition treatments in alkaline soil. Soil pH and NO_3^--N concentration were significantly affected by biochar amendment (soil pH increased by 1.43–1.56, 0.57–0.70, and 0.29–0.37 units for acidic vegetable soil, neutral rice soil, and alkaline soil, respectively). Thus, biochar amendment could be used as an effective management practice for mitigating N_2O emissions from acidic and alkaline soils.").

[159] Nabuurs G., *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-64 ("Biochar properties vary with feedstock, production conditions and post production treatments, so mitigation and agronomic benefits are maximised when biochars are chosen to suit the application context (Mašek et al. 2018). A recent assessment finds greatest economic potential (up to US$100 tCO_2 y^{-1}) between 2020 and 2050 to be in Asia and the developing Pacific (793 $MtCO_2$ yr^{-1}) followed by Developed Countries (447 $MtCO_2$ yr^{-1}) (Roe et al. 2021)."). *See also* Roe S., Streck C., Beach R., Busch J., Chapman M., Diaoglou V., Depperman A., *et al*. (2021) Land-based measures to mitigate climate change: Potential and feasibility by country, GLOBAL CHANGE BIOLOGY 27, 6043.

[160] Grados D., Butterbach-Bahl K., van Groenigen K. J., Olesen J. E., van Groenigen J. W., & Abalos D. (2022) Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems, ENVTL. RESEARCH LETTERS 17:114024, 6 ("Considerable N_2O reductions were found for biochar amendment (−26.6%), optimization of fertilizer rate (−31.2%), slow- or controlled release fertilizer (−33.0%), nitrification inhibitors (−44.1%), urease inhibitors (−22.5%), combined use of nitrification and urease inhibitors (−49.4%), and drip irrigation (−26.5%). The use of greater frequency of fertilizer application (−5.4% [−26.9 to +22.3%]), crop residue removal (−2.6% [−14.2 to +10.6%]), and lime amendment (−9.0% [−30.8 to +19.7%]) led to mixed results, though across all studies minor reductions in N_2O emissions were observed. The use of organic fertilizer (+4.8% [−7.2 to +18.4%]), diversified crop rotation (+8.6% [−17.1 to +42.3%]), deep fertilization (+18.6% [−6.9 to +51.1%]), no tillage (+11.7% [−8.9 to +37.0%]) or reduced tillage (+3.7%[−11.1to+21.0%]) resulted in marginal increases in N_2O emissions as compared to standard practices. The use of cover crops increased N_2O emission by +36.7% (figure 2).").

[161] The values here are converted from table 1 of Winiwarter W., *et al*. (2018) *Technical Opportunities to Reduce Global Anthropogenic Emissions of Nitrous Oxide*, ENVIRON. RES. LETT. 13:1–12, 3. The exchange rate used for the conversion is EUR 1 = US$ 1.1450, the Euro Foreign Exchange Reference Rate as of 31 December 2018 published by the European Central Bank.

[162] SOP, *SOP, Save Our Planet* (*last accessed* 27 August 2024).

[163] Borgonovo F., *et al*. (2019) *Improving the sustainability of dairy slurry with a commercial additive treatment*, MDPI, SUSTAINABILITY ("N_2O, CO_2, and CH_4 emissions, from the treated slurry, were respectively 100%, 22.9% and 21.5% lower than the control at T4 when the emission peaks were recorded."). *See also* Peterson C., *et al*. (2020) *Effects of SOP Lagoon Additive on Gaseous Emissions from Stored Liquid Dairy Manure*, SUSTAINABILITY 12: 1–17, 12 ("Compared to the CONT, the HIGH treatment achieved average emission reductions of 22.7% and 14.7% for CH_4

and CO_2, respectively ($p < 0.05$). The HIGH vs CONT treatment also showed an emission reduction of 45.4% for N_2O.").

[164] Maris S. C., *et al.* (2021) *Reducing N Fertilization without Yield Penalties in Maize with a Commercially Available Seed Dressing*, AGRONOMY 11:1–19, 2 ("Gypsum is a relatively cheap and common mineral amendment, with a range of favorable effects on both soil physical and chemical properties. Gypsum also provides calcium (Ca) and sulfur (S) to plants. The improvement of soil conditions and relative plant responses have the potential to increase crop yields, by increasing root system development and establishment, and enhancing water and nutrients uptake by plants.").

[165] Maris S. C., *et al.* (2021) *Reducing N Fertilization without Yield Penalties in Maize with a Commercially Available Seed Dressing*, AGRONOMY 11:1–19, 14 ("Our results confirmed that the main driver for GHG emissions is the N-fertilizer rate: the application of increasing rate of N fertilizer led to increased N_2O emissions due to enhanced availability of N in soil, thus stimulating nitrification and/or denitrification microbial activity. In detail, decreasing N-fertilization from 100% to 70% decreased N_2O emissions by 509 mg N-N_2O m^{-2} y^{-1}.").

[166] Maris S. C., *et al.* (2021) *Reducing N Fertilization without Yield Penalties in Maize with a Commercially Available Seed Dressing*, AGRONOMY 11:1–19, 15 ("The yield performance of SCM with 70% N-fertilization, which was similar to that of Control with 100% N-fertilization (as reported earlier), suggests an indirect potential of this product for reducing N_2O emissions (~23%) from intensively managed maize by reducing N-fertilization without losing yield.").

[167] Balafoutis A., *et al.* (2017) *Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics*, SUSTAINABILITY 11: 1–28, 7 ("VRNA is executed by either applying a prescription map that was designed after receiving data from the field using mainly canopy sensors that identify the status of the crop and correlate it with nutrient needs or by combining the recording and reacting procedure on-the-go, meaning simultaneously inorganic fertilizers are distributed in the field using two main technologies, the spinner or centrifugal spreaders that are based on a conveyer belt or chain that transfers the material (granules) from the hopper until it falls on one or more spinning disks throwing the particles into the field and the pneumatic spreaders that use airflow which divides the granules over a piped spreading boom for uniform distribution.").

[168] Houlton B. Z. *et al.* (2019) *A World of Cobenefits: Solving the Global Nitrogen Challenge*, EARTH'S FUTURE 7:865–872, 867 ("Improving nitrogen-use efficiency can be accomplished by adopting a mix of agricultural practices and technologies. Generally, this target includes shifting fertilizer technologies and practices, using improved crop varieties, and boosting soil health to increase the fraction of nitrogen fertilizer that enters agricultural products, creating incentives for improved nitrogen management and following the 4Rs of nitrogen fertilizer application: right rate, right type, right placement, and right timing (Johnston & Bruulsema, 2014; Zhang et al., 2015)."); Balafoutis A., *et al.* (2017) *Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics*, SUSTAINABILITY 11: 1–28, 9 ("At a certain point, the benefits of an added unit of nitrogen (i.e., extra crop yield) barely outweigh the costs of this unit, and an economic optimum is reached. This economic optimum is found at lower application rates than the yield optimum. By fertilising each management zone near the economic optimum, higher returns can be achieved. Thus, the highest returns for VRNA are expected on fields with high and spatially variable nutrient requirements. Excessive application of nitrogen fertilisation decreases financial returns and increases the potential for nitrogen leaching into the environment. Insufficient application can reduce yields and net farm income.").

[169] Balafoutis A., *et al.* (2017) *Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics*, SUSTAINABILITY 11: 1–28, 9 ("Tekin (2010) estimated that VRNA can increase wheat production between 1% and 10% offering savings in nitrogen fertilisation between 4% and 37%.").

[170] The values here are converted from table 1 of Winiwarter W., *et al*. (2018) *Technical Opportunities to Reduce Global Anthropogenic Emissions of Nitrous Oxide*, ENVIRON. RES. LETT. 13:1–12, 3. The exchange rate used for the

conversion is EUR 1 = US$ 1.1450, the Euro Foreign Exchange Reference Rate as of 31 December 2018 published by the European Central Bank.

[171] Southern Star Team (29 April 2022) *TEAGASC: Why clover is a win-win for both the farmer and the environment*. The Southern Star ("Using clover achieves a reduction in nitrous oxide by lowering the chemical N fertiliser use up to 100 kg N/ha. Using clover to reduce the use of chemical nitrogen can reduce nitrous oxide emissions by up to 40% on a dairy farm due to reduced chemical N fertiliser application."; "On dairy farms, research has shown that using clover can increase milk solids production 20-48 kg/cow per year and increase net farm profit by €108-€305/ha. On suckler farms, profitability increased by 14% for the grass/clover system when compared to a 'conventional' pasture system.").

[172] Panchasara H., Samrat N. H., & Islam N. (2021) *Greenhouse Gas Emissions Trends and Mitigation Measures in Australian Agriculture Sector—A Review*, AGRICULTURE 11:1–16, 13 ("Use minimum tillage for cropping has the potential to minimizes organic matter breakdown and the release of N_2O.").

[173] Panchasara H., Samrat N. H., & Islam, N. (2021) *Greenhouse Gas Emissions Trends and Mitigation Measures in Australian Agriculture Sector—A Review*, AGRICULTURE 11:1–16, 12 ("Furthermore, they estimated the potential of county-scale GHG reductions due to converting from conventional tillage to no-tillage practices. Their results showed that a mean reduction of 1477 kg CO_2-eq ha^{-1} $year^{-1}$ is possible which includes N_2O, SOC and CH_4 flux reductions of 549 kg, 945 kg, 17 kg CO_2-eq ha^{-1} $year^{-1}$, respectively, with a standard deviation of 605 kg CO_2-eq ha^{-1} $year^{-1}$.").

[174] Guenet B., *et al.* (2021) *Can N_2O emissions offset the benefits from soil organic carbon storage?* GLOBAL CHANGE BIOLOGY 27:237–256, 242 ("There has been considerable discussion as to whether the increased SOC in soil under zero tillage, especially near the surface, might increase N_2O emissions, because: (a) increased organic matter content can increase N_2O release (Mei et al., 2018), either because of increased energy supply to denitrifying organisms or because increased biological activity utilizes oxygen in soil, thus possibly leading to anoxic conditions at some microsites and (b) reducing tillage can be associated in the short term with a less porous soil structure, conducive of anoxy (Linn & Doran, 1984; Table 1). However, increased anoxia may have the opposite effect on N_2O emissions by accelerating N_2O reduction to N_2 as recently shown. This is due to the complex soil physical structure creating anoxic microsites that may simultaneously produce more N_2O but also accelerate N_2O reduction to N_2 (Buchen et al., 2019; Parkin, 1987).").

[175] Forabosco F., Chitchyan Zh., & Mantovani R. (2017) *Methane, nitrous oxide emissions and mitigation strategies for livestock in developing countries: A review*, SOUTH AFRICAN J. OF ANIMAL SCIENCE 47(3):268–280, 276–277 ("Unmanaged manure and slurry can cause eutrophication and contamination of surface water, leaching of nitrates, degradation of natural resources and GHG in the form of CH_4 and N_2O (direct and indirect emissions), NH_3, and other toxic gases (Hristov et al., 2013a)… Correct management of manure has been extensively demonstrated to be the most important tool that can minimize losses due to CH_4 and N_2O volatilization and runoff (Petersen et al., 2013; Sommer et al., 2013). Manure from ruminants and non-ruminants can be treated by various methods for improved handling, nutrient use and energy generation. In developing countries, simple techniques such as piling, compacting and covering the manure have positive effects on reducing emissions and nutrient losses. For example, covering solid manure with straw or plastic sheets reduces, in general, both CH_4 and N_2O emissions, whereas covering liquid manure stores is adopted mainly to reduce NH_3 emissions (Petersen et al., 2013). N_2O emissions from liquid slurry are minimal during storage, unless a surface crust is present (VanderZaag et al., 2009)… Modern technology, such as manure separation, anaerobic digestion, aeration, use of additives and inhibitors (Petersen et al., 2012; Zaman & Nguyen, 2012; Gebrezgabher et al., 2015; Kinyua et al., 2016), to treat manure and slurry from ruminates and nonruminants, may not represent a feasible option to reduce GHG emissions in developing countries. The main reasons are high costs, low accessibility, high technology required, lack of knowledge, and insufficient legislation."); Herrero M., *et al.* (2016). *Greenhouse gas mitigation potentials in the livestock sector*, NATURE CLIMATE CHANGE 6:452–461, 453 ("Taking an aggregate view of the sector, and using all LCA sources of emissions, animal feed production accounts for about 45% of the sector's emissions, with about half of these emissions related to fertilization of feed crops and

pastures (manure and fertilizer included). The remaining animal feed emissions are shared between energy use and land use. Enteric fermentation contributes about 40% of total emissions, followed by manure storage and processing (~10% of emissions)."); Hou Y., Velthof G. R., & Oenema O. (2014) *Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment*, GLOBAL CHANGE BIOLOGY 21:1293–1312, 1304 (Clearly, lowering CP content in animal feed is an effective strategy to reduce NH_3 emissions in the entire management chain (Figs. 4–6). Lowering dietary CP decreases the N content of animal excreta. This is more pronounced for urine than for faeces (Fig. 2). Urinary N is mainly in the form of urea and is easily converted into NH_3 by the enzyme urease present in faeces (Smits *et al.*, 1995, Canh *et al.*, 1998a; Misselbrook *et al.*, 2005a; Galassi *et al.*, 2010). Lowering CP feed also decreases the pH of the manure (Fig. 2a), which decreases the risk of NH_3 emissions.").

[176] Rivera J. E. & Chara J. (2021) *CH_4 and N_2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems,* FRONTIERS IN SUSTAINABLE FOOD SYSTEMS 5: 657936, 7, 9 ("The most promising options for reducing GHG emissions at the livestock management level include improving animal production through dietary changes. Nitrogen (N) excretion rates, which affect N_2O emissions from manure, are based on dry matter consumption (DMC) and its N content (Vergé et al., 2012). Therefore, dietary manipulation to optimize protein consumption, and thus improve the efficiency of N utilization, is one of the most effective measures to reduce emissions from manure (Novak and Fiorelli, 2010). The more nitrogen used by an animal, the less will be excreted; it is recommended that an adjusted amount of nutrients be offered in the diet to meet the animal's requirements, thus, avoiding increased excretion (Schils et al., 2008). This condition can occur in both high-supply N systems such as dairy production, as well as in tropical systems where the N supply in the feed is reduced."; "Diet manipulation can also reduce CH_4 emissions from manure. In a study by Lombardi et al. (2021) the supplementation of grazing beef steers with maize grain lowered CH_4 emissions of dung from 4.0 to 1.7 g CH_4-C/m^2. Dung from supplemented animals had higher N, starch, and DM content, which resulted in lower CH_4 emissions compared with dung from non-supplemented animals. Results from this study indicated that the initial water content may control the CH_4 emissions, since rainfall events after dung crusting did not increase the CH_4 fluxes from dung patches (Zhu et al., 2018). On the other hand, these authors state that supplementation with maize grain can thus have dual benefits in cattle production, through maximizing body weight gain in grazing steers (18% more) by improving the efficiency of utilization of nutrients (dietary N in particular) and through decreasing the total amount and/or the intensity of GHG emissions. In addition, the improvement in N utilization efficiency may reduce N_2O emissions from urine deposition (Cai et al., 2017).").

[177] Forabosco F., Chitchyan Zh., & Mantovani R. (2017) *Methane, nitrous oxide emissions and mitigation strategies for livestock in developing countries: A review*, SOUTH AFRICAN J. OF ANIMAL SCIENCE 47(3):268–280, 275 ("When the digestibility of forages increases, enteric fermentation and manure production are reduced, and consequently the emissions of CH_4 and N_2O decrease. For example, when legume silage replaces grass silage in the diet, because of the lower fibre content and the presence of high digestible organic nitrogen, CH_4 and N_2O emissions are reduced (Hristov et al., 2013a). Smallholders in mixed crop livestock systems in Africa and Asia are characterized by livestock herds with many unproductive animals, small quantities of high-quality feed and large quantities of low-quality feed. An effective mitigation strategy is to reduce the number of animals (keeping only the best animals) and provide feed with higher digestibility, reserving the low-quality feed for other purposes (e.g. bedding). This strategy would increase productivity and reduce CH_4 and N_2O emissions.").

[178] Rivera J. E. & Chara J. (2021) *CH_4 and N_2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems,* FRONTIERS IN SUSTAINABLE FOOD SYSTEMS 5: 657936, 11("Biochar can also decrease CH_4 emission or increase CH_4 oxidation *via* increasing soil aeration and reducing soil bulk density, but some compounds contained in biochar may also inhibit the activity of methanotrophs and increase CH_4 emission (van Zwieten et al., 2010)."); *see also* Harrison B., Moo Z., Perez-Agredano E., Gao S., Zhang X., & Ryals R. (2024) *Biochar-composting substantially reduces methane and air pollutant emissions from dairy manure*, ENVTL. RES. LETTERS 19: 014081, 1 ("[W]e conducted a full-scale composting study at a dairy farm and monitored the emission of greenhouse gases (CO_2, CH_4, N_2O) and air pollutants (H_2S, VOCs, NO_x, NH_3) from compost piles amended with

or without biochar. We found that amending compost with biochar significantly reduced total CH_4 emissions by 58% (±22%) and cut H_2S, VOCs, and NO_x emissions by 67% (±24%), 61% (±19%) and 70% (±22%), respectively. We attribute this reduction in emissions to improved oxygen diffusion from the porous biochar and the adsorption of gas precursors to the biochar surface.”).

[179] Rivera J. E. & Chara J. (2021) *CH_4 and N_2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems,* FRONTIERS IN SUSTAINABLE FOOD SYSTEMS 5: 657936, 9 (“The incorporation of shrubs and trees in pastures in the called silvopastoral systems (SPS) can also contribute to reduce emissions by improving soil cover and health and by increasing the quality of the diet (Chará et al. 2019)… On the other hand, such systems can modify emissions in feces by the presence of dung beetles that limit the interactions of manure with mineral soil, restricting substrates for nitrification and denitrification processes (Slade et al., 2016). Studies in different regions of Colombia have shown that SPSs have greater abundance, diversity, and activity of beetles than treeless pastures (Giraldo et al., 2011; Montoya-Molina et al., 2016). According to Slade et al. (2016) the presence of beetles in livestock systems reduces N_2O emissions by 14.7% and CH_4 emissions by 17%. Another effect of these systems is the increased N partitioning into dung relative to urine as this has shown to reduce N_2O emissions from pastures, since the emission factor for dung is lower than that for urine (Luo et al. 2018).”).

[180] Cui X., *et al.* (2021) Global mapping of crop-specific emission factors highlights hotspots of nitrous oxide mitigation, NATURE FOOD 2:886–893, 888 (“For all crops, climatic and edaphic variables were the most important drivers, while management-related variables were less important at this scale of analysis (Fig. 2). The link between EFs and environmental variables was consistent with factors known to affect metabolic activities of N-related microbial communities and N_2O production in soils [22]. Large-scale molecular-level investigations reveal that the geographic distributions of nitrifiers and denitrifiers were significantly explained by climatic and edaphic variables [23], controlling N and carbon substrates, oxygen availability, enzymatic activity and metabolic energy sources.”); *See also* Wang H., Yan Z., Ju X., Song X., Zhang J., Li S., & Zhu-Barker X. (2023) *Quantifying nitrous oxide production rates from nitrification and denitrification under various moisture conditions in agricultural soils: Laboratory study and literature synthesis*, FRONTIERS IN MICROBIOLOGY 13:1110151, 1 (“Biogenic nitrous oxide (N_2O) from nitrification and denitrification in agricultural soils is a major source of N_2O in the atmosphere, and its flux changes significantly with soil moisture condition. However, the quantitative relationship between N_2O production from different pathways (i.e., nitrification vs. denitrification) and soil moisture content remains elusive, limiting our ability of predicting future agricultural N_2O emissions under changing environment…. Results showed that as soil moisture increased, N_2O production rates of nitrification and denitrification first increased and then decreased, with the peak rates occurring between 80 and 95% WFPS. By contrast, the dominant N_2O production pathway switched from nitrification to denitrification between 60 and 70% WFPS. Furthermore, the synthetic data elucidated that moisture content was the major driver controlling the relative contributions of nitrification and denitrification to N_2O production, while NH_4^+ and NO_3^- concentrations mainly determined the N_2O production rates from each pathway. The moisture treatments with broad contents and narrow gradient were required to capture the comprehensive response of soil N_2O production rate to moisture change, and the response is essential for accurately predicting N_2O emission from agricultural soils under climate change scenarios.”); Larios A. D., Brar S. K., Avalos Ramirez A., Godbout S., Sandoval-Salas F., & Palacios J. H. (2016) *Challenges in the measurement of emissions of nitrous oxide and methane from livestock sector*, REVIEWS OF ENVTL. BIOTECHNOLOGY 15:285–297, 285 (“Over the past two decades, the interest to decrease the emission levels of greenhouse gases (GHGs) has increased. The livestock sector has been put under continuous supervision and regulation because it is an important source of GHG emissions. In 2012, it was estimated that 3.46 Gton CO_2-eq was released from this sector, methane (CH_4) being the gas with the highest contribution (43 %), followed by nitrous oxide (21 %). In order to determine real emissions, it is necessary to use precise and reproducible measuring methods which can be complex and expensive. The challenges in these methods are focused on achieving an accurate assessment and monitoring of gas emissions, developing monitoring systems for the continuous measurement and implementation of methodologies for their validation in field in order to understand the complex nature of environmental variables affecting gas production.”); Kenmou L. & Amanatidou E. (2023) Factors Affecting Nitrous Oxide Emissions from Activated Sludge Wastewater Treatment Plants—A Review, Resources 12(10):114, 114 (“The main factors affecting N_2O emissions are the dissolved oxygen concentration (DO),

the nitrite accumulation, the rapidly changing process conditions, the substrate composition and COD/N ratio, the pH, and the temperature. Low DO in the nitrification process results in higher N_2O emissions, whereas high aeration rate in the nitration/anammox process results in higher N_2O production. High DO in the denitrification inhibits the N_2O reductase synthesis/activity, leading to N_2O accumulation. High nitrite accumulation in both the nitrification and denitrification processes leads to high N_2O emissions. Transient DO changes and rapid shifts in pH result in high N_2O production. Ammonia shock loads leads to incomplete nitrification, resulting in NO_2^- accumulation and N_2O formation. Limiting the biodegradable substrate hinders complete denitrification, leading to high N_2O production. A COD/N ratio above 4 results in 20–30% of the nitrogen load being N_2O emissions. Maximum N_2O production at low pH (pH = 6) was observed during nitrification/denitrification and at high pH (pH = 8) during partial nitrification. High temperature enhances the denitrification kinetics but produces more N_2O emissions.").

[181] *See e.g.*, Cui X., *et al.* (2021) *Global mapping of crop-specific emission factors highlights hotspots of nitrous oxide mitigation*, NATURE FOOD 2:886–893, 886 ("Mitigating soil nitrous oxide (N_2O) emissions is essential for staying below a 2 °C warming threshold. However, accurate assessments of mitigation potential are limited by uncertainty and variability in direct emission factors (EFs). To assess where and why EFs differ, we created high-resolution maps of crop-specific EFs based on 1,507 georeferenced field observations. Here, using a data-driven approach, we show that EFs vary by two orders of magnitude over space. At global and regional scales, such variation is primarily driven by climatic and edaphic factors rather than the well-recognized management practices. Combining spatially explicit EFs with N surplus information, we conclude that global mitigation potential without compromising crop production is 30% (95% confidence interval, 17–53%) of direct soil emissions of N_2O, equivalent to the entire direct soil emissions of China and the United States combined. Two-thirds (65%) of the mitigation potential could be achieved on one-fifth of the global harvested area, mainly located in humid subtropical climates and across gleysols and acrisols."); Mathivanan G. P., Eysholdt M., Zinnbauer M., Rosemann C., & Fuß R.(2021) *New N_2O emission factors for crop residues and fertiliser inputs to agricultural soils in Germany*, AGRICULTURE, ECOSYSTEMS AND ENVIRONMENT 322:107640, 1 ("Direct agricultural N_2O emissions in Germany have so far been estimated using the default Tier 1 emission factor of 1% (0.3–3%) in accordance with the IPCC's default methodology. Since direct N_2O emissions is a "key category" in the German National Greenhouse Gas Inventory, the IPCC recommends the use of country-specific emission factors or models. With the aim of deriving country-specific and stratified N_2O emission factors, a meta-analysis was conducted using data collected from 71 individual studies comprising 676 separate emission measurements taken at 43 locations across Germany. A Bayesian generalised linear mixed-effects modelling approach was used to model N_2O fluxes and derive emission factors. In contrast to what is suggested by the 2019 Refinement to the 2006 IPCC Guidelines, the model results did not support a distinction being made between emission factors for synthetic and organic fertilisers. Instead, a model based on four environmental zones roughly representing the north-west, north-east, south-east and south-west parts of the country was developed. It was used to derive district-wise emission factors for direct N_2O emissions and revealed that northern districts had relatively lower emission factors than southern districts. The district-wise emission factors ranged from 0.38% to 0.92%. The national implied emission factor for direct N_2O emissions from managed agricultural soils was 0.62% (0.43–0.85%). Accordingly, the estimate of German national GHG emissions from agriculture in 2015 is 8.59% (calculated with global warming potentials from IPCC's fifth assessment report) lower than the estimate reported in the 2021 inventory submission to UNFCCC."); Grace P., De Rosa D., Shcherbak I., Strazzaboso A., Rowlings D., Scheer C., Barton L., Wang W., Schwenke G., Armstrong R., Porter I., & Bell M. (2023) *Revised emission factors for estimating direct nitrous oxide emissions from nitrogen inputs in Australia's agricultural production systems: a meta-analysis*, SOIL RESEARCH 62:SR23070, 1 ("The average EF from all N sources (excluding EEFs) was 0.57%. Industry-based EFs for synthetic N fertiliser (excluding EEFs) ranged from 0.17% (non-irrigated pasture) to 1.77% (sugar cane), with an average Australia-wide EF of 0.70%. Emission factors were independent of topsoil organic carbon content, bulk density and pH. The revised EF for the non-irrigated cropping (grains) industry is now 0.41%; however, geographically-defined EFs are recommended. Urea was the most common N source with an average EF of 0.72% compared to urine (0.20%), dung (0.06%) and organo-mineral mixtures (0.26%). The EF for synthetic N fertilisers in rainfed environments increased by 0.16% for every 100 mm over 300 mm mean annual rainfall. For each additional 50 kg N ha^{-1} of synthetic fertiliser, EFs increased by 0.13%, 0.31% and 0.38% for the horticulture, irrigated and high rainfall non-irrigated

cropping industries, respectively. The use of 3,4 dimethylpyrazole-phosphate (DMPP) produced significant reductions in EFs of 55%, 80% and 84% for the horticulture, nonirrigated and irrigated cropping industries, respectively.").

[182] Kanter D., Ogle S. M., & Winiwarter W. (2020) *Building on Paris: integrating nitrous oxide mitigation into future climate policy*, CURRENT OPINION IN ENVTL. SUSTAINABILITY 47:7–12, 8 ("The most widely used EFs for N_2O were developed by the Intergovernmental Panel on Climate Change (IPCC) and assume a linear relationship between N application rates and N_2O emissions [12]. For example, a 1% EF is applied to synthetic N fertilizer rates to estimate direct emissions (i.e. for every 100 kg N applied, 1 kg of N_2O is emitted).").

[183] Kanter D., Ogle S. M., Winiwarter W. (2020) *Building on Paris: integrating nitrous oxide mitigation into future climate policy*, CURRENT OPINION IN ENVTL. SUSTAINABILITY 47:7–12, 8 ("However, using a nonlinear EF for upland grain crops derived via meta-analysis, a reduction from 50 kg N ha^{-1} to zero would reduce emissions by 0.37 kg N_2O-N ha^{-1}, while a reduction from 300 kg N ha^{-1} to 250 kg N ha^{-1} would reduce emissions by 0.84 kg N_2O-N ha^{-1} , suggesting greater mitigation potential in regions with higher N application rates [14].").

[184] Kanter D., Ogle S. M., Winiwarter W. (2020) *Building on Paris: integrating nitrous oxide mitigation into future climate policy*, CURRENT OPINION IN ENVTL. SUSTAINABILITY 47:7–12, 8 ("This not only has implications for how agricultural N_2O emissions are estimated in national and regional inventories, it also suggests that in regions of the world where many farms apply N at very low rates, such as sub-Saharan Africa and parts of Eastern Europe, increases in N fertilizer use would generate relatively small increases in agricultural N_2O emissions depending on the agronomic practices and associated N use efficiency of the crops [15]. Similarly, even moderate decreases in highly fertilized regions could trigger significant emissions reductions.").

[185] Liu L., *et al.* (2022) *KGML-ag: a modeling framework of knowledge-guided machine learning to simulate agroecosystems: a case study of estimating N_2O emission using data from mesocosm experiments*, GEOSCIENTIFIC MODEL DEVELOPMENT 15:2839–2858, 2849("The results from eight different models showed that KGML-ag1 comparing with other pure ML models consistently provided the lowest RMSE (3.59–3.94 mg Nm^{-2} d^{-1} , 1.14– 1.23 mg Nm Nm^{-2} d^{-2} and 0.84–0.89 mg Nm^{-2} d^{-3}) and highest r^2 (0.78–0.81, 0.48–0.56 and 0.23–0.31) for N_2O fluxes, slope and curvature, respectively (Fig. 4). This indicated that KGML-ag1 outperformed other pure ML models in capturing both the magnitude and dynamics of N_2O flux. Meanwhile, we have calculated the uncertainty of mesocosm measurement due to converting hourly data to daily data during 30–80 d by using augmented values minus the mean of the augmented values with lower and upper limits being −10.2 and 10.4 mg Nm^{-2} d^{-1} , respectively (standard deviation = 1.4 mg Nm^{-2} d^{-1}). KGML-ag1 during the same period has comparable uncertainties based on ensemble simulations with lower and upper limits being −14.4 and 15.2 mg Nm^{-2} d^{-1} , respectively (calculated by ensemble values minus the mean of ensemble values; standard deviation of 1.3 mg Nm^{-2} d^{-1}). KGML-ag2 presented slightly better mean scores for N_2O flux predictions than KGMLag1, but worse scores for slope and curvature and larger uncertainties. This proved the hypothesis discussed in Sect. 3.2 that KGML-ag2 did not benefit the magnitude and dynamics predictions of N_2O flux with its more complex structure and less connections between IMVs.").

[186] Liu, L. *et al.* (2022) *KGML-ag: a modeling framework of knowledge-guided machine learning to simulate agroecosystems: a case study of estimating N_2O emission using data from mesocosm experiments*, GEOSCIENTIFIC MODEL DEVELOPMENT 15:2839–2858, 2853 ("To better explain the time series predictions of N_2O flux (Figs. S1, 2 and 3), we separated the observations of each year into three periods: leading period (before N_2O increasing), increasing period (increasing to the peak) and decreasing period (peak decreasing to near zero). During the leading period, both NH_4^+ and CO_2 were increasing immediately in the following few days following urea N fertilizer application, indicating that urea was decomposing into NH_4^+ and CO_2 in soil water. With accumulating NH_4^+ in soil, nitrification started producing NO_3^- and consuming O_2. N_2O did not respond to the fertilizer immediately due to enough O_2 in soil. Then when the soil became sufficiently hypoxic, N_2O fluxes entered an increasing period with N_2O being produced by nitrification and denitrification processes. CO_2 fluxes were relatively low and NH_4^+ kept decreasing during this period. Finally, when soil NH_4^+ was exhausted and NO_3^- started decreasing due to denitrification, N_2O fluxes then entered the decreasing period. CO_2 flux was related to urea decomposition during the leading period and

was more closely related to O_2 demand in other periods. The KGML-ag predictions of N_2O and IMV captured the three periods and transition points, demonstrating the connections between those variables following the description as above (Figs. 3 and S5).").

[187] Feng R. & Fang X. (2022) *Devoting Attention to China's Burgeoning Industrial N2O Emissions*, ENVTL. SCI. & TECH. 56(9):5299–5301, 5300 ("Working toward industrial emission abatement, China participated in a program named Clean Development Mechanism (CDM) around 2007,[17] drawing on thermal and/or catalytic decomposition.[18][19]").

[188] Tong Q., *et al.* (2020) *Scenario analysis on abating industrial process greenhouse gas emissions from adipic acid production in China*, PETROLEUM SCIENCE 14:1171–1179, 1172 ("In 2005–2012, the average annual growth rate of adipic acid production was 20.3% and the average annual growth rate of N_2O emissions was 15.6%. During this period, the growth rate of N_2O emissions from the adipic acid production process was significantly lower than the growth rate of adipic acid production. The main reason is that in 2010–2012, based on the cooperation of the international Clean Development Mechanism project, the adipic acid industry conducted a series of N_2O emission abatement activities (Tong 2011; Lee et al. 2011; Yan et al. 2018; Lu 2009) so that the implied emission factors decreased. However, due to the suspension of international cooperation in 2013 (Tong et al. 2012), domestic companies were unable to withstand high abatement costs (Tong et al. 2012; Frutos et al. 2018), and the implied emission factor in 2014 rebounded to beyond 2005 level.").

[189] Feng R. & Fang X. (2022) *Devoting Attention to China's Burgeoning Industrial N_2O Emissions*, ENVTL. SCI. & TECH. 56(9):5299–5301, 5300 ("Furthermore, CDM projects only covered a small portion of N_2O-emitting chemical plants in China (https://cdm.unfccc.int). Even if all equipped installations in CDM were exploited at full capacity, a maximum 85 Gg (approximately 12%) of China's industrial N_2O emissions could be eliminated relative to total emissions in 2018.").

[190] Tong Q., *et al.* (2020) *Scenario analysis on abating industrial process greenhouse gas emissions from adipic acid production in China*, PETROLEUM SCIENCE 14:1171–1179, 1174 ("Since N_2O is not a conventional pollutant, there is no mandatory N_2O emission abatement requirement in China … .").

[191] Tong, Q. *et al.* (2020) *Scenario analysis on abating industrial process greenhouse gas emissions from adipic acid production in China*, PETROLEUM SCIENCE 14:1171–1179, 1178 ("Through the integration of the above two emission abatement approaches, China's adipic acid production process can achieve increasingly significant N_2O emission abatement effects. Compared to the baseline scenario, by 2030, the N_2O emission abatements of the three emission abatement scenarios can reach 207–399 kt and the emission abatement ratios can reach 32.5%–62.6%. By 2050, the N_2O emission abatements for the three emission abatement scenarios can reach 387–540 kt and the emission abatement ratios can reach 71.4%–99.6%.").

[192] Nabuurs G., *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-109 ("The agricultural sector throughout the world is influenced by many policies that affect production practices, crop choices and land use. It is difficult to quantify the effect of these policies on reference level GHG emissions from the sector, as well as the cost estimates presented in Sections 7.4 and 7.5. The presence of significant subsidy programs intended to improve farmer welfare and rural livelihoods makes it more difficult to implement regulatory programs aimed at reducing net emissions in agriculture, however, it may increase the potential to implement new subsidy programs that encourage practices aimed at reducing net emissions (medium confidence). For instance, in the USA, crop insurance can influence both crop choices and land use (Claassen et al. 2017; Miao et al. 2016), both of which will affect emission trends. Regulations to limit nutrient applications have not been widely considered, however, federal subsidy programs have been implemented to encourage farmers to conduct nutrient management planning.").

[193] Kishore A., Alvi M., & Krupnik T. J. (2021) *Development of balanced nutrient management innovations in South Asia: Perspectives from Bangladesh, India, Nepal, and Sri Lanka*, GLOBAL FOOD SECURITY 28:1–8, 1 ("In the past, fertilizer subsidies helped promote the use of fertilizers and contributed to significant increases in yields (Morris et al., 2007), but in recent years, their contribution to productivity increase (Kapur, 2011; Sharma, 2012) and overall agricultural growth and poverty reduction has declined over time (Fan et al., 2007) even as the subsidy bill keeps growing.").

[194] Kishore A., Alvi M., & Krupnik T. J. (2021) *Development of balanced nutrient management innovations in South Asia: Perspectives from Bangladesh, India, Nepal, and Sri Lanka*, GLOBAL FOOD SECURITY 28:1–8, 1–2 ("Apart from exacting high economic costs, the existing subsidy regimes in Bangladesh, India, Nepal, and Sri Lanka also incentivize excessive application of urea and underapplication of P and K fertilizers (at least in India and Nepal), micronutrients, and organic inputs; contribute to soil degradation, contamination of groundwater, and emission of greenhouse gases (Chand and Pandey, 2009; Prasad, 2009; Liu et al., 2014); discourage product innovation by fertilizer companies; and crowd out productive investments in agricultural research and development (Gulati and Banerjee, 2016).").

Gulati A. & Banerjee P. (2015) *Rationalising Fertiliser Subsidy in India: Key Issues and Policy Options*, Working Paper 307 – Indian Council for Research on International and Economic Relations, 22 ("Cumulative estimated investment increased from Rs.252.58 billion in 2000-01 to Rs.281.09 billion in 2010-11. Hence, the capacity creation was also meagre – around 2.3 MMT after the introduction of the new investment policy for urea plants in 2008. 36 (The capacity existing after the revamp of some urea plants is given in Annex 4). In the last two years, however, the cumulative investment in fertiliser sector went up to Rs. 350.90 billion mainly due to the increase in estimated investment in the public sector (Rs. 54.55 billion) in 2012-13. 37 That might be one of the reasons why the share of imports in total fertiliser consumption declined in the last two years (Chart 7)").

[195] Kaarthiyen G. M. & Suresh A. (2019) *A Study on Understanding the Adoption of Water Saving Technology: A Case Study of Drip Irrigation*, INT'L J. OF RECENT TECH. & ENG'G 7:1123–1130, 1129 ("Each farmers will have multiple reasons for non-adopting to drip irrigation. 57% of farmers (31 farmers) have not adopted to drip irrigation because of high initial cost, 26 farmers (48%) have not adopted to drip irrigation system because of less water source and 16 farmers out of 54 (30%) have not adopted to drip irrigation because they didn't got subsidy from the government and 14 farmers have not adopted because the pipes are getting damaged by the animals."); Wu Y., Wang E., & Miao C. (2019) *Fertilizer Use in China: The Role of Agricultural Support Policies*, SUSTAINABILITY 11: 1–23, 3–4 ("Agricultural support programs may drive agricultural intensification and contribute to the increased use of chemical fertilizers. In order to receive more subsidies, farmers, in addition to expanding cropping area, would make more intensive use of fertilizers, pesticides, irrigation water, and fossil fuels, to increase yields [30]. A strong positive association between agricultural support and the intensity of fertilizer use has been found to exist in OECD countries [17,18], as well as in developing countries including China [31,32]. Based on an analysis of 40 countries, Harold and Runge [33] found that when the Producer Subsidy Estimate (PSE)—a measure of the value of transfers to producers from consumers and taxpayers resulting from a given set of agricultural policies—increased by one unit, commercial fertilizer use would increase by 15.4 kg per hectare per year. On the other hand, research found that during the 15 years after the government abolished price subsidies and input subsidies in the 1980s, the use of fertilizers and pesticides saw a significant decline in New Zealand [34]. Using a general equilibrium approach, Taheripour, Khanna, and Nelson [35] also found that, in an open economy, removing agricultural subsidies and imposing nitrogen reduction subsidies can effectively enhance welfare and reduce nitrogen pollution."); Claassen R., Langpap C., & Wu J. (2015). *Impacts of Federal Crop Insurance on Land Use and Environmental Quality*, Presentation at the 2015 Agricultural & Applied Economics Association and Western Agricultural Economics Associate Annual Meeting, 25 ("Our results indicate that the more meaningful impact of revenue insurance will be on crop choice and therefore on crop rotation patterns. Total acreage of corn is predicted to increase by roughly 3%, whereas the amount of acres planted with wheat will decrease by about 16%. Accordingly, the acreage planted with most crop rotations involving corn increases, by about 4% for continuous corn and 9% for corn-corn-soybeans. On the other hand, acres of continuous wheat decline by as much as 14%. These changes in cropping systems will have small effects on agricultural runoff and environmental quality, with the largest predicted impact being a roughly 7% increase in wind erosion. In sum, we find

that crop insurance has likely had small effects on land use, and modest impacts on crop rotation systems and therefore on environmental quality in the U.S. Corn Belt region.”).

[196] American Farming Bureau Federation (2021) *Farm Bureau National Policies 2021*, 64, 72 (“We oppose: 2.1. Resource planning on farms and ranches being codified into federal law unless it is totally and unquestionably proven to be voluntary, confidential, based on proven performance standards, and providing acceptable immunity for producers who have exercised good faith compliance with all applicable laws and regulations; 2.2. Attempts by state or federal agencies to develop non-voluntary environmental management systems as a regulatory or permitting framework; 2.3. Implementation of commercial fertilizer management plans or whole farm management plans to address natural resource concerns on our farms; U.S. policies affecting agriculture should be designed to: 4.6. Continue to improve the environment through expanded incentives to encourage voluntary soil conservation, water and air quality programs, and advanced technological and biotechnological procedures that are based on sound science and are economically feasible;”).

[197] American Farming Bureau Federation (2021) *Farm Bureau National Policies 2021,* 170 (“We support: 2.3. Compensation to farmers for planting crops or adopting farming practices that keep carbon in the soil or plant material; 2.4. Alternative energy sources, which will minimize atmospheric pollution; 2.5. Incentives to industries seeking to become more energy efficient or to reduce emissions of identifiable atmospheric pollution and the means of preventing it; 2.6. Market-based solutions, rather than federal or state emission limits, being used to achieve a reduction in greenhouse gas (GHG) emissions from any sources;”).

[198] Florida Farm Bureau Federation (2021) *2021 Policy Book*, 21, 88, 99 (“We believe that all persons have the ability and responsibility to improve the society in which they live. Sharing one’s talents through voluntary efforts has been keystone to America.”; “52. Florida Cattlemen’s Association’s Voluntary Assessment We support the Florida Cattlemen’s Association’s (FCA) program for funding environmental research, education, and legal defense on a voluntary basis. (BEEF)”; “247. Federal Environmental Self Audit We support voluntary environmental self-audits, the incentive based program for self-policing discovery, disclosure and correction to prevent violation of federal environmental protection laws, conducted by owners and operators. The environmental audit and documents related to an environmental self-audit, for individual farms or operations, should be confidential and exempt from Florida public records laws. We support legislation prohibiting the use of self-audit documents and reporting by third parties as a basis for citizen enforcement and nuisance suits.”; “271. Payment for Environmental Services: We support voluntary payment for environmental services programs which allow for diversification and sustainability of agricultural operations and provide environmental benefits such as dispersed water storage, filtration, and wildlife habitat. Contracts for these environmental services programs should contain provisions that allow the land to revert back to the original condition, without penalty, or additional state or federal permit requirements for the agricultural operation or landowner.”).

[199] Kaeding D. (25 October 2019) *Long Road Ahead For Rolling Out Manure Restrictions In Eastern Wisconsin*, WISCONSIN PUBLIC RADIO (*last visited* 19 July 2024) (“Bonness estimates around 80 to 90 percent of the county's roughly 130 dairy farms are no longer spreading on the thinnest soils. She said land has been removed from manure application, but they've also discovered areas where soils are thicker. The county hopes to determine all areas with the most shallows soils by next June. But Bonness said it could take years to implement new standards with the amount of work to be done in the face of limited resources and funding.”).

[200] Mengistu F. & Assefa E. (2019) *Farmers’ decision to adopt watershed management practices in Gibe basin, southwest Ethiopia*, INT’L SOIL & WATER CONSERVATION RES 7:376–387, 384 (“Extension services had a significant positive effect on soil bund, stone faced soil bund, grass strips cultivation with mostly soil bund, and on compost application. We also found a significant positive correlation of households’ access to training related to watershed management practices with stone faced soil bund, grass strip with mostly soil bund and agroforestry practices, suggesting that access to knowledge and awareness creation are important in accelerating the adoption of knowledge intensive technologies. This result agreed with the studies by Adesina, Mbila, Nkamleu, and Endamana (2000), Tiwari,

et al. (2008b), and Asfaw and Neka (2017), who reported intervention through training and extension services is a means of creating awareness and provision of support for the adoption of new technologies."); Danso-Abbeam G., Dagunga G., & Ehiakpor D. S. (2019) *Adoption of Zai technology for soil fertility management: evidence from Upper East region, Ghana*, J. of Econ. Structures 8:1–14, 12 ("The results of the study suggest that to boost food crop productivity through improved agrarian technology, access to extension service should be strengthened through adequate provision of logistics, in-house training and recruitment of agents.").

[201] Kishore A., Alvi M., & Krupnik, T. J. (2021) *Development of balanced nutrient management innovations in South Asia: Perspectives from Bangladesh, India, Nepal, and Sri Lanka*, GLOBAL FOOD SECURITY 28:1–8, 2–3 ("Studies show that giving soil tests–based recommendations to farmers without adequate education on what test data mean or how to make use of them has a negligible effect on both farmers' understanding of crop nutrient requirements and their actual use (Fishman et al., 2016). Research in Odisha and Gujarat states of India shows that simplifying SHCs and making them more user-friendly led to significant improvements in farmers' comprehension of soil health information (Singh et al., 2018; Cole and Sharma, 2017). Repeated engagement with farmers through call centers or personal visits by extension or fertilizer company staff have been shown to result in increases in understanding of SHCs and a small, but significant, increase in the adoption of more balanced nutrient application recommendations (Cole and Sharma, 2017). Experience deploying app-based fertilizer recommendations to large numbers of farmers in different parts of India and Bangladesh also shows the need for a repeated engagement with farmers and field-level extension agents to increase understanding of soil fertility and create impact (Singh et al., 2018)."); Boulanger, P., *et al.* (2022) *Effectiveness of fertilizer policy reforms to enhance food security in Kenya: a macro–micro simulation analysis*, APPLIED ECON. 54:841–861, 842 ("One of the most critical drivers of low agricultural productivity is the lagging use of modern inputs, especially fertilizers, and the lack of access to technology (Mutea, Rist, and Jacobi 2020). Traditionally, Kenya attempted to solve the issue through public input subsidy programmes. However, the review of recent evidence questioned the effectiveness of this public support (Jayne et al. 2013). As a result, the Kenyan government is studying alternative approaches to price subsidies in order to increase the ability of all farmers to purchase the right inputs at the right time. The government is proposing a complete restructuring of the current subsidy schemes over the period of 2019–2029 (Government of Kenya 2019). In this context of sustainable agricultural transformation, it has facilitated the establishment of two fertilizer plants through Public–Private Partnership (PPP) projects. At the same time, various actions aim at improving the benefits of using fertilizers such as the development of extension programmes (Jayne et al. 2013). The aim of these policies is to increase food supply through higher productivity and ultimately improve food security and welfare.").

[202] Smith L. E. D., & Siciliano G. (2015) *A comprehensive review of constraints to improved management of fertilizers in China and mitigation of diffuse water pollution from agriculture*, AGRICULTURE, ECOSYSTEMS, AND ENVIRONMENT 209:15–25, 22 ("Farmers' attitude towards risk and the degree to which their decision making is risk averse will depend on a range of factors. These include: the level, security and degree of diversification of farm household income; the quality of a farmer's information and knowledge about output risk (as affected by weather, pests, disease, irrigation shortage etc.), agricultural input use and effectiveness, and environmental risk; the degree of trust in extension agents or other sources of advice; and the farmer's level of education.").

[203] Davidson E. A., Suddick E., Rice C. W., & Prokopy L. S. (2015) *More Food, Low Pollution (Mo Fo Lo Po): A Grand Challenge for the 21st Century*, J. OF ENVTL. QUALITY 44:305–311, 306–307, 308–309 ("3. Agricultural extension services have diminishing reach, and sociological research shows that most US farmers now obtain the majority of their information about management from family members, retailers, and private sector crop advisors (Fig. 2). Hence, the most effective role of extension may now be to train the retailers and crop advisors so that these private sector stakeholders may then become the trusted sources of up-to-date nutrient management information for the majority of farmers; 4. The younger generation of farmers is increasingly well-educated and is willing to consider new technologies and to try Web-based decision support tools; nevertheless, abandoning their parents' and grandparents' tried-and-true practices remains a barrier. Most farmers have significant demands on their time and labor. Learning and adopting new practices requires that the proposed innovations are compelling, easily implemented, and worth their time."; "Osmond et al. (2015) synthesized results from informant surveys in 13 watersheds of the USDA

Conservation Effects Assessment Project (CEAP) study, supplemented with field surveys from three nutrient-impaired watersheds in North Carolina. The CEAP results indicate that farmers generally did not follow nutrient management plans or basic soil test recommendations even when they had them. Reasons included of trust in university extension recommendations for N applications, preference for fertilizer dealer recommendations, and a perception of abundant N as insurance. In the North Carolina study, the data indicated that many farmers were making their fertilizer application decisions based on little technical advice. More successes were achieved in CEAP watersheds where there were project investments in education, outreach to small farmer groups, and financial incentives such as cost sharing. The authors warn that without better dialogue with farmers, as well as meaningful investment in strategies that reward farmers for taking what they perceive as risks relative to nutrient reduction, little progress in true adoption of nutrient management is probable.").

[204] Cui X., Shang Z., Xia L., Xu R., Adalibieke W., Zhan X., Smith P., & Zhou F. (2022) *Deceleration of Cropland-N_2O Emissions in China and Future Mitigation Potentials*, ENVTL. SCI. & TECH. 56(7):4665–4675, 4672 ("Considering that farmers generally have a low level of education in China, government support (such as technical training and demonstration trials in the major crop production areas) is essential to convince farmers the effectiveness of these new technologies, and meanwhile agricultural subsidies should be accordingly afforded.[54]").

[205] Fleming D. A., Brown, P., & Knook, J. (2019*) Barriers to adoption of win– win mitigation farm practices: evidence from New Zealand pastoral farmers*, Motu Technical Paper, 7–8 ("'It requires a coordinated approach to make it work. The standard of pasture management needs to be improved with greater attention to detail and not every farm has the capability to achieve this. Applying more N is simpler and hence more effective for just some people/systems' (about D2). This reasoning is a combination of two barriers: 'Inadequate managerial capability', as indicated by the lack of capability; and 'Unsureness about practicality', as indicated by the suggestion that, because of ease and convenience, others may avoid the practice)."); Chen X., Zeng D., Xu Y, & Fan X. (2018) *Perceptions, Risk Attitude and Organic Fertilizer Investment: Evidence from Rice and Banana Farmers in Guangxi, China*, SUSTAINABILITY 10:1–14, 2 ("In Denmark, Case et al. [30] show that soil structure improvement is the most important reason to use organic fertilizer, while unpleasant odor, uncertainty in nutrient content, and difficulty in planning and use are the major barriers. Using data from multiple European countries, Hou et al. [32] found that perceived high cost and long payback period are the main barriers of investment in organic fertilizer. In addition, farmers in developing countries are generally found to be risk averse against production and climate volatilities [33–35], which can influence their investment in inputs and agricultural technologies [36–42]. For instance, production uncertainty may lead to the overuse of fertilizers [43,44]. As soil improvement may potentially safeguard crop growth against production risks [12], it may incentivize risk-averse farmers to switch towards organic fertilizer.").

[206] Cortes-Acosta, S., *et al.* (2019) *Identifying barriers to adoption of "no-cost" greenhouse gas mitigation practices in pastoral systems*, Motu Working Paper 19-10, 48, 54 ("Smeaton et al. (2011) use a farm-scale model to suggest the existence of farming systems that both increase farm profits and have modest emissions. These systems include farming practices that decrease stocking rates, with change in their composition, or that increase the use efficiency of nitrogen fertilisers. According to these authors, such emission-friendly farming practices are not widely implemented because it is complex to do so and the biophysical characteristics (such as soil type) of some farms limit their intake.); Rochecouste et al. (2015) evidence this barrier in their study of drivers for growing legumes in Australia. Growing legumes on a rotational basis retains nitrogen in the soil and allows a boost to future grain yields, thus reducing the need for fertilisers. However, farmers perceive the growing of legumes as highly seasonally dependent compared to other crops – for instance, cereals obtain better yields than legumes during dry years. At the same time, this decision is balanced by the level of input prices and output prices. If fertiliser prices are high, farmers may assign a higher value to the benefits from growing legumes, which will depend on legume prices."); Barnes, A. P., *et al.* (2019) *Exploring the adoption of precision agricultural technologies: a cross regional study of EU farmers*, LAND USE POL'Y 80:163–174, 171 ("The statement on perceived profitability, 'I am too uncertain of the effects of PAT to invest in it' is negative and significant for those who adopt VRNT bundles, compared to MG only. This may be indicative of the differences in the type of technology adopted, where one is embodied knowledge and the other information intensive.

Specifically, the perception of the PAT having an effect is more explicitly embodied in VRNT which encourages more active engagement compared to MG, which is passive, and therefore the perceived effect of adoption is much lower.").

[207] Griffin T., Shanoyan A, Miller N. J. (2017) *Farm's Sequence of Adoption of Information-intensive Precision Agricultural Technology*, APPLIED ENG'G IN AGRICULTURE 33:521–527, 525 ("In summary, the results provide four particularly important insights regarding the pattern of on-farm adoption and utilization of PA technologies. First, there is less than 6% likelihood that current non-adopters will adopt any PA technology in the following year. Second, out of all current users of single technologies (VR; YM; PSS) the users of VR are most likely to adopt an additional type of technology in the following year, which is likely to be YM exclusively. Current YM users are not likely to adopt any other technology in the following year. Third, the current users of the YM-only bundle are more likely to adopt the complete bundle of technologies than any other single technology adopter. Fourth, non-adopters are most likely to adopt YM as their first PA technology, while YM users are more likely to adopt PSS than VR.").

[208] Brown P. & Roper S. (2017) *Innovation and networks in New Zealand farming*, AUSTRALIAN J. OF AGRICULTURAL AND RESOURCE ECON. 61:422–442, 435–438 ("Respondents were asked either about the number of individuals with whom they discussed farm finances or environmental performance of the farm, and results are disaggregated by network type, and responses are aggregated. Whether focusing on pro-environmental management practices or novel farm technologies, innovators and early adopters each have larger professional networks than laggards ($P < 0.01$). In the case of pro-environmental management practices, innovators and early adopters also have statistically larger networks than the late majority ($P < 0.10$). However, we cannot distinguish network sizes of innovators from those of early adopters statistically.").

[209] Smith L. E. D., & Siciliano, G. (2015) *A comprehensive review of constraints to improved management of fertilizers in China and mitigation of diffuse water pollution from agriculture*, AGRICULTURE, ECOSYSTEMS, AND ENVIRONMENT 209:15–25, 22 ("Sheriff, 2005, argues that trust and a farmer's perceptions of agronomic advice will influence the rate of fertilizer application. If farmers perceive that the suggested rate of fertilization is too conservative, or that the recommendations of extension advisors under-estimate crop response in their fields, they may over-apply relative to the recommendation. Evidence is cited that farmers systematically over-estimate the impact of additional nitrogen relative to agronomists' recommendations (Sherrif, 2005).").

[210] Nabuurs G., *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU), in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-70–7-71 ("Considering that Asia and developing Pacific, and Developed Countries accounted for the greatest share of global nitrogen fertiliser use, it is not surprising that these regions are estimated to have greatest economic mitigation potential (up to US$100 tCO_2-eq^{-1}) between 2020 and 2050, at 161.8 and 37.1 $MtCO_2$-eq yr^{-1} respectively (using the IPCC AR4 GWP_{100} value for N_2O) (Roe et al. 2021).").

[211] Nabuurs G., *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU), in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-70 ("Sub-Saharan Africa has one of the lowest global fertiliser consumption rates, with increased fertiliser use suggested as necessary to meet projected future food requirements (Mueller et al. 2012; Adam et al. 2020; ten 44 Berge et al. 2019; Falconnier et al. 2020).").

[212] Nabuurs G., *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU), in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-26 ("Latest data indicate agricultural N_2O emission increases in most regions, though variation between databases prevents definitive conclusions on trends, with Africa, Southern Asia, and Eastern Asia suggested to have had greatest growth since 1990 according to EDGAR (Crippa 27 et al. 2021), FAOSTAT (FAO 2021a) and USEPA (USEPA 2019) data respectively."),

[213] Nabuurs G., *et al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU), in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers D. & Ravindranath N. H. (eds.), 7-26 ("However, all databases

indicate that emissions declined in Eurasia and Europe from 1990 levels, in accordance with specific environmental regulations put in place since the late 1980s (Tubiello 2019; European Environment Agency 2020; Tian et al. 2020), but generally suggest increases in both regions since 31 2010.").

[214] Wolf M. J, Emerson J. W., Esty D. C., de Sherbinin, A., *et al.* (2022) *2022 Environmental Performance Index* 55 ("Nitrous oxide and methane emissions present a unique threat to Earth's climate system. While sources of carbon dioxide and fluorinated gases have well-researched and sustainable replacements, there are no concrete pathways to fully eliminate agricultural emissions of methane and nitrous oxide. The Global West is the only region decreasing both methane and nitrous oxide, but emissions in other regions outweigh this progress.").

[215] The White House (28 May 2024) *FACT SHEET: Biden-Harris Administration Announces New Principles for High-Integrity Voluntary Carbon Markets*, Statements and Releases ("As part of this commitment, the Biden-Harris Administration is today releasing a Joint Statement of Policy and new Principles for Responsible Participation in Voluntary Carbon Markets (VCMs) that codify the U.S. government's approach to advance high-integrity VCMs.").

[216] Climate Action Reserve (*last accessed* 27 August 2024) has developed a U.S. Adipic Acid Production Protocol (2020), a China Adipic Acid Production Protocol (2023) and a U.S. Nitric Acid Production Protocol (2019).

[217] Spalding-Fecher R., Achanta A. N., Erickson P., Haites E., Lazarus M., Pahuja N., Pandey N., Seres S., & Tewari R. (2012) *Assessing the Impact of the Clean Development Mechanism: Report commissioned by the High-level Panel on the CDM Policy Dialogue*, 71 ("Researchers have found that this activity shifting, or emission leakage, is likely to have occurred with adipic acid facilities, with production shifting from capped regions and facilities that emit fewer N_2O emissions to CDM project facilities that gain CERs for reducing N_2O emissions.").

[218] Climate Action Reserve (2023) *China Adipic Acid Production Protocol Version 1.0*, 20 ("This protocol utilizes a mandatory minimum 90% abatement efficiency in the baseline for all AAPs in China to protect against leakage incentives. By only crediting incremental emissions beyond the 90% baseline, the economic incentives remain attractive but do not appear to create the same skewed incentives as under the CDM. AAPs that have no previous N_2O abatement or enhanced existing technology to abatement above 90% are required to utilize a 90% baseline abatement efficiency (AEBL). However, if an AAP has previous N_2O abatement greater than 90% and enhances the technology further, the baseline should be adjusted based on the maximum level of abatement achieved over a 5-year lookback period from the project start date and is established for the life of the project.").

[219] Climate Action Reserve (2023) *China Adipic Acid Production Protocol Version 1.0*, 11–12 ("Project AAPs are not allowed to increase production above what market conditions would otherwise justify due solely to the objective of increasing carbon revenues. That is, the sole reason for increasing production would be to generate more credits, not sell more adipic acid… To mitigate against this risk, credit issuance for adipic acid production levels that exceed the AAP's nameplate capacity for production levels as of the project start date as defined by the AAP's latest government filing, such as an Environmental Impact Assessment Report (EIA) or performance check report, will not be considered without first notifying the Reserve.").

[220] Climate Action Reserve (2023) *China Adipic Acid Production Protocol Version 1.0*, 12 ("In instances where an AAP seeks to increase its production capacity more than 10% above nameplate capacity and wishes to receive credits for the increased production, the project developer shall notify the Reserve immediately to discuss options for demonstrating that the increased production is in response to market demand and not an attempt to increase production solely for the purpose of generating additional credits. For example, the Reserve may request the project developer to provide documentation that the additional adipic acid that has been produced above an 110% level has been sold into the market (e.g., invoices, contracts) as deemed acceptable to a verifier.").

[221] Locus Agricultural Solutions. *CarbonNOW Program* (*last visited* on 18 July 2024).

[222] Ali, B. (26 Jan. 2021) *Locus Ag partners with Bluesource to market carbon credits*, AGRIINVESTOR.COM (*last accessed on* 27 August 2024) ("CarbonNow is the start-up's program for farmland owners that takes them through the process of sequestering and measuring carbon captured in their soil in line with a desired methodology, through to having that carbon capture verified by third parties and then marketed and sold by a retailer, such as Bluesource.")

[223] Locus Agricultural Solutions. *Rhizolizer® supercharges nutrient uptake*, RHIZOLIZER PRODUCT OVERVIEW (*last accessed on* 27 August 2024) ("Adding Rhizolizer® to a farm's input strategy is not only a smart choice, it's vital for increasing yields. The superior, strategically selected microbial strains found in the Rhizolizer® product line boost row crop yields by unlocking unused inputs and other soil nutrients, creating a stronger root system, increasing nutrient uptake, and enhancing plant vigor. Because the strains are endophytic, they create a symbiotic relationship with the plant for long-lasting benefits. • Rhizolizer® Duo – Powerful DUO combination of Locus AG's novel endophytic fungus and bacteria.").

[224] Locus Agricultural Solutions, *Carbon Now™: Grow More Food & Fight Climate Change* (BOLD Awards, 2019) (*see* Slide 15, stating that Rhizolizer decreases N_2O emissions by 75-85% in corn, 87% in citrus, and 60% in potatoes separately and in addition to any fertilizer input reductions).

[225] UNEP Ozone Secretariat (17 February 2017) *Frequently asked questions relating to the Kigali Amendment to the Montreal Protocol* at 2 (*see* Table 1 on HFC phase-down schedule under Kigali Amendment, providing that the HFC/HCFC emissions must plateau at 85% by 2036 for non-A5 (developed countries) Parties, 80% by 2045 for A5 Group 1 Parties, and 85% by 2047 for A5 Group 2 Parties). *See also* KIGALI AMENDMENT TO THE MONTREAL PROTOCOL.

[226] MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER [MONTREAL PROTOCOL], ART. 2, ¶ 10 ("(a) Based on the assessments made pursuant to Article 6 of this Protocol and in accordance with the procedure set out in Article 9 of the Convention, the Parties may decide: (i) Whether any substances, and if so which, should be added to or removed from any annex to this Protocol; and (ii) The mechanism, scope and timing of the control measures that should apply to those substances."); *See also* LONDON AMENDMENT TO MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER [London Amendment], Part I ("Paragraph 10 (b) of Article 2 of the Protocol shall be deleted. and paragraph 10 (a) of Article 2 shall became paragraph 10.").

[227] The Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer adopted decisions on the process and other considerations for controlling new substances. See, e.g., Decision IX/24: Control of new substances with ozone-depleting potential (1997); Decision X/8: New substances with ozone-depleting potential (1998); Decision XI/19: Assessment of new substances (1999); Decision XI/20: Procedure for new substances (1999); Decision XIII/5: Procedures for assessing the ozone-depleting potential of new substances that may be damaging to the ozone layer (2001). *See also* VIENNA CONVENTION FOR THE PROTECTION OF THE OZONE LAYER [Vienna Convention], Arts. 3(1) and (2), Annexes I and II. Note that Annex I(4) of the Vienna Convention includes nitrous oxide as one of the listed "chemical substances of natural and anthropogenic origin, not listed in order of priority, [that] are thought to have the potential to modify the chemical and physical properties of the ozone layer."

[228] World Meteorological Organization (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 99 ("Several recent publications have found that global N_2O emission increases have been accelerating over the last two decades and by now exceed some of the highest projections (Thompson et al., 2019; Tian et al., 2020; IPCC, 2021).").

[229] World Meteorological Organization (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 99 ("Anthropogenic emissions N_2O were driving that increase, and these alone (43%, Tian et al., 2020) were equal to more than two times the ODP-weighted emissions from all CFCs in 2020. For context, when compared to the CFC emission peak from 1987, those 2020 anthropogenic N_2O emissions were equal to more than 20 % the ODP-weighted emissions from CFCs in that year.").

[230] World Meteorological Organization (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 393 ("A reduction in future N_2O emissions from that in the baseline scenario (SSP2-4.5) to that in the SSP scenario with the strongest N_2O mitigation (SSP1-1.9) results in a 0.5 DU increase in ozone averaged over 2020 to 2070, or about one-quarter of the impact of eliminating all emissions from controlled ODSs beginning in 2023. This emission reduction also leads to a radiative forcing reduction of 43 mW m^{-2} averaged over 2023–2100. The magnitude of this N_2O reduction represents a decrease in anthropogenic N_2O emissions of 3% compared with the baseline scenario when averaged over 2020 –2070.").

[231] World Meteorological Organization (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 258 ("Therefore, in general, the ozone return date is expected to be later if there are increases in N_2O or earlier if there are decreases in N_2O. However, the effect of future increases in N_2O varies with altitude and also depends on the temporal evolution of other GHGs.").

[232] World Meteorological Organization (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, 394 (*see* Figure 7-1 showing that N_2O emissions reduction to SSP1-1.9 results in a decrease in radiative forcing of about 0.04 W m^{-2} while eliminating all high-GWP HFC emissions results in a decrease in radiative forcing of about 0.07 Wm^{-2}).

[233] UNEP (2014) *Phasing-Out Methyl Bromide in Developing Countries: A success story and its challenges*, at 5 ("A major barrier when introducing alternatives was that this process often had to be carried out against the background of an established system, with infrastructure, equipment, and supply chains already in place. In the agricultural sector, there are large numbers of farmers and different crops scattered across countries. The process followed for selecting the most suitable alternatives, where these were first trialed and demonstrated, and where key stakeholders were involved, contributed to creating a good level of acceptance towards the alternatives proposed. A wide approach is necessary, including registration and commercial availability of successful alternatives, at a feasible cost. Training was an essential component of the phase-out process, and should be continued.").

[234] INMS (2022) *Developing national action plans to address nitrogen pollution: A preliminary guidance document*, INMS Working Paper 1-2022, 1 ("[A] national action plan is a coherent and transparent national and subnational-level roadmap for addressing N losses to the environment. More specifically, it is the combination of an overarching vision for sustainable N management based on an assessment of national and subnational N flows and policies, coupled with measurable, time bound objectives integrated across multiple sectors, and an enforceable implementation and evaluation strategy. A national action plan should deliver a number of co-benefits: avoiding multiple environmental and human health impacts and generating important economic savings via more efficient and sustainable use of N inputs.").

[235] PARIS AGREEMENT, Art. 4 ("1. In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty. 2. Each Party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions.").

[236] UNFCCC Secretariat (2021) *Nationally determined contributions under the Paris Agreement, Synthesis report by the secretariat*, ¶ 5(d) ("Parties have increased the coverage of sectors and GHGs: 99.2 per cent of their total GHG emissions are covered compared with 97.8 per cent for the previous NDCs; and all cover CO_2 emissions, almost all cover CH_4 and N_2O emissions, most cover HFC emissions and many cover PFC, SF_6 and NF_3 emissions."; *see* Footnote 3 for the definition of 'almost all': 'almost all' for more than 90 per cent").

[237] Kanter D. R., Ogle S. M., & Winiwarter W. (2020) *Building on Paris: integrating nitrous oxide mitigation into future climate policy*, ENVTL. SUSTAINABILITY 47:7–12, 7 ("Some Parties to the UNFCCC, such as the European Union, have considered N_2O as part of their overall GHG target development, but only one country, Uruguay, includes explicit mitigation targets for N_2O.").

[238] Kanter D. R., Ogle S. M., & Winiwarter W. (2020) *Building on Paris: integrating nitrous oxide mitigation into future climate policy*, ENVTL. SUSTAINABILITY 47:7–12, 10 ("In another example, Uruguay's food sector is responsible for close to three quarters of their national GHG emissions, with N_2O contributing one third of national emissions. Consequently, its first NDC set an economy-wide target of reducing N_2O emissions intensity by 51%–57% below1990 levels by 2030, and 37%–43% in the livestock sector.").

[239] Gobierno de México (2022) *Contribución Determinada a Nivel Nacional Actualización 2022*, 13 ("Finalmente, México implementa una Estrategia Nacional de Enfriamiento, como parte del cumplimiento de la Enmienda de Kigali, que promueve acciones de reducción de HFC y participa en el Grupo de Acción Climática del Ácido Nítrico (NACAG) para mitigación de óxido nitroso (N_2O).").

[240] Cames M., *et al.* (2016). *How Additional is the Clean Development Mechanism?*, CLlMA.B.3/SERl2013/0026r, at 95 ("Under the CDM, four projects were registered. Two projects are located in China, one is in Brazil and one in South Korea. All four CDM plants had no abatement installed before project implementation and applied either thermal or catalytic abatement. The four implemented CDM plants cover only a part of the adipic acid production in developing countries because the applicable CDM methodology AM0021 is limited to plants that started commercial operation before 2005.").

[241] Farand C. (02 October 2020). *Nigeria, Jamaica Bring Closure to the Kyoto Protocol Era, in Last-Minute Dash*, CLIMATE HOME NEWS (*last accessed* on 27 August 2024) ("The Doha Amendment will come into force this year after Nigeria became the 144th country to ratify the climate treaty on Friday, in a last-minute scramble to tie the loose ends of the Kyoto Protocol era. UN Climate Change confirmed Nigeria had formally endorsed the climate treaty hours before a deadline that required 144 of the 192 signatories to ratify the deal for it to come into force on 31 December 2020 — a day before it is due to expire.").

[242] McKenna P., Pike L., & Northrop K. (06 August 2020). *'Super-Pollutant' Emitted by 11 Chinese Chemical Plants Could Equal a Climate Catastrophe*, INSIDE CLIMATE NEWS (*last accessed* on 27 August 2024) ("A 2014 report by the Institute for Applied Ecology in Germany concluded that the Shenma and Liaoyang plants faced 'a high risk of stopping GHG [greenhouse gas] abatement.' The companies had no financial incentive to abate after the value of CDM credits plummeted and there were no government regulations requiring abatement, the report noted. The report also stated that by 2014 there were five other adipic acid plants in China that were not part of the Clean Development Mechanism. 'None of them abates N_2O emissions,' the report concluded.).

[243] GOTHENBURG PROTOCOL TO ABATE ACIDIFICATION, EUTROPHICATION, AND GROUND-LEVEL OZONE [Gothenburg Protocol]. Art. 3, ¶ 1, Annex II ("Each Party having an emission reduction commitment in any table in annex II shall reduce and maintain the reduction in its annual emissions in accordance with that commitment and the timescales specified in that annex. Each Party shall, as a minimum, control its annual emissions of polluting compounds in accordance with the obligations in annex II.").

[244] GOTHENBURG PROTOCOL, Art. 3, ¶ 8 ("Each Party shall, subject to paragraph 10: (a)Apply, as a minimum, the ammonia control measures specified in annex IX.").

[245] GOTHENBURG PROTOCOL, Annex IX, ¶ 4 ("Within one year from the date of entry into force of the present Protocol for it, a Party shall take such steps as are feasible to limit ammonia emissions from the use of solid fertilizers based on urea.").

[246] GOTHENBURG PROTOCOL, Annex IX, ¶ 5 ("Within one year from the date of entry into force of the present Protocol for it, a Party shall prohibit the use of ammonium carbonate fertilizers.").

[247] GOTHENBURG PROTOCOL, Annex IX, ¶ 6 ("Each Party shall ensure that low-emission slurry application techniques (as listed in guidance document V adopted by the Executive Body at its seventeenth session (decision 1999/1) and any amendments thereto) that have been shown to reduce emissions by at least 30% compared to the reference specified in that guidance document are used as far as the Party in question considers them applicable, taking account of local soil and geomorphological conditions, slurry type and farm structure. ").

[248] GOTHENBURG PROTOCOL, Annex IX, ¶ 8 ("Within one year from the date of entry into force of the present Protocol for it, a Party shall use for new slurry stores on large pig and poultry farms of 2,000 fattening pigs or 750 sows or 40,000 poultry, low-emission storage systems or techniques that have been shown to reduce emissions by 40% or more compared to the reference (as listed in the guidance document referred to in paragraph 6), or other systems or techniques with a demonstrably equivalent efficiency.[6]").

[249] GOTHENBURG PROTOCOL, Art. 3, ¶ 8 ("Each Party shall, subject to paragraph 10: … (b) Apply, where it considers it appropriate, best available techniques for preventing and reducing ammonia emissions, as listed in guidance adopted by the Executive Body. Special attention should be given to reductions of ammonia emissions from significant sources of ammonia for that Party.").

[250] U.N. Economic Commission for Europe (UNECE) (2020) *UN mobilises action to tackle $200bn per year waste and pollution caused by global nitrogen losses* (*last accessed* 27 August 2024) ("To address these pollution problems globally, a new Guidance Document on Integrated Sustainable Nitrogen Management, has, on 18 December 2020, been adopted by Parties to the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention).").

[251] Task Force on Reactive Nitrogen (TFRN) (2020) *Draft Guidance document on integrated sustainable nitrogen management*, ¶ 12.

[252] TFRN (2020) *Draft Guidance document on integrated sustainable nitrogen management*, ¶ 362 ("Placement of N and P fertilizer directly into the soil close to the rooting zone of the crop can be associated with enhanced N and P uptake, lower losses of N to air and N and P to water and a lower overall N and P requirement compared with broadcast spreading on the seedbed or subsequent 'top dressing'. The approach includes fertilizer injection methods, but may also be achieved by immediate incorporation of fertilizer into the soil. Placement within the soil reduces direct exposure to the air and the risk of losses by ammonia volatilization.").

[253] TFRN (2020) *Draft Guidance document on integrated sustainable nitrogen management*, ¶ 336 ("While usually associated with inorganic fertilizers, nitrification inhibitors can be added to livestock slurries just prior to application to delay the conversion of the slurry ammonium to nitrate, which is more susceptible to losses through denitrification, run-off and leaching.").

[254] Sutton M. A., Howard C. M., Mason K. E., Brownlie W. J., Cordovil C. M. d. S. (2022) *Nitrogen Opportunities for Agriculture, Food & Environment. UNECE Guidance Document on Integrated Sustainable Nitrogen Management*, 1 ("The present guidance document is focused on agriculture in the context of the food system, and includes specific information on the principles and measures that can reduce emissions to the air of ammonia (NH_3), nitrogen oxides (NO_X), nitrous oxide (N_2O) and N_2, plus nitrate (NO_3^-) and other Nr leaching to water and total N loss.").

[255] Sutton M. A., Howard C. M., Mason K. E., Brownlie W. J., Cordovil C. M. d. S. (2022) *Nitrogen Opportunities for Agriculture, Food & Environment. UNECE Guidance Document on Integrated Sustainable Nitrogen Management*, 1 ("The accompanying discussion of basic principles will help strengthen the development of future strategies for pollution and sustainable development, and the establishment of coherent "packages of measures" that maximize the synergies.").

[256] Aan den Toorn S. I., Worrel, E., van den Broek M. A. (2021) *How much can combinations of measures reduce methane and nitrous oxide emissions from European livestock husbandry and feed cultivation?*, J. OF CLEANER PRODUCTION 304:1–14, 1 ("The European Union (EU28) has outlined a strategy to reduce greenhouse gas (GHG) emissions to net-zero by 2050 in line in order to limiting the global temperature increase to 1.5 C (European Commission, 2018a). Besides dramatically reducing CO_2 emissions, methane (CH_4) and nitrous oxide (N_2O) emissions from agriculture must also reduce from 461 Mt CO_2-eq in 2016 to 284 or even 237 Mt CO_2-eq in 2050 (European Commission, 2018b; European Environment Agency, 2018).").

[257] European Commission (2020) *Farm to Fork Strategy for a fair, healthy, and environmentally-friendly food system,* 9 ("The Commission will act to reduce nutrient losses by at least 50%, while ensuring that there is no deterioration in soil fertility. This will reduce the use of fertilisers by at least 20% by 2030.").

[258] European Commission (2020) *Farm to Fork Strategy for a fair, healthy, and environmentally-friendly food system*, 10 ("This approach will help to reach the objective of at least 25% of the EU's agricultural land under organic farming by 2030 and a significant increase in organic aquaculture.").

[259] Aan den Toorn S. I., Worrel E., van den Broek M. A. (2021) *How much can combinations of measures reduce methane and nitrous oxide emissions from European livestock husbandry and feed cultivation?* J. OF CLEANER PRODUCTION 304:1–14, 12 ("In general, the combinations with a high mitigation potential show a pattern of a few core mitigation measures targeting the largest emission flows combined with a wider set of other measures. For beef and dairy cattle in particular, the measure'1CFeed 3NOP additive 'is critical for high reductions as it strongly reduces enteric fermentation. The number of measures in a combination also appear to influence how much can be mitigated. Our study pathway estimates that implementing the highest mitigating combination for each category can potentially reduce meat and dairy related CH_4 by 62% and N_2O by 32%, resulting in an overall 54% reduction in CO_2-eq.").

[260] Council of the European Communities (1991) COUNCIL DIRECTIVE OF 21 MAY 1991 CONCERNING URBAN WASTE WATER TREATMENT (91 /271 /EEC), Art. 5, ¶ 4, Annex II ("4. Alternatively, requirements for individual plants set out in paragraphs 2 and 3 above need not apply in sensitive areas where it can be shown that the minimum percentage of reduction of the overall load entering all urban waste water treatment plants in that area is at least 75 % for total phosphorus and at least 75 % for total nitrogen.;" "A. Sensitive areas 1) A water body must be identified as a sensitive area if it falls into one of the following groups: a) natural freshwater lakes, other freshwater bodies, estuaries and coastal waters which are found to be eutrophic or which in the near future may become eutrophic if protective action is not taken. The following elements might be taken into account when considering which nutrient should be reduced by further treatment: i. lakes and streams reaching lakes/reservoirs/closed bays which are found to have a poor water exchange, whereby accumulation may take place. In these areas, the removal of phosphorus should be included unless it can be demonstrated that the removal will have no effect on the level of eutrophication. Where discharges from large agglomerations are made, the removal of nitrogen may also be considered; ….").

[261] Council of the European Communities (1986) COUNCIL DIRECTIVE OF 12 JUNE 1986 ON THE PROTECTION OF THE ENVIRONMENT, AND IN PARTICULAR OF THE SOIL, WHEN SEWAGE SLUDGE IS USED IN AGRICULTURE (86/278/EEC), *Preamble* ("Whereas the aim of this Directive is to regulate the use of sewage sludge in agriculture in such a way as to prevent harmful effects on soil, vegetation, animals and man, while encouraging its correct use.").

[262] Council of the European Communities (1986) COUNCIL DIRECTIVE OF 12 JUNE 1986 ON THE PROTECTION OF THE ENVIRONMENT, AND IN PARTICULAR OF THE SOIL, WHEN SEWAGE SLUDGE IS USED IN AGRICULTURE (86/278/EEC), Art. 8 ("Article 8. The following rules shall be observed when using sludge: — the sludge shall be used in such a way that account is taken of the nutrient needs of the plants and that the quality of the soil and of the surface and ground water is not impaired, — where sludge is used on soils of which the pH is below 6 , Member Stated shall take into account the increased mobility and availability to the crop of heavy metals and shall, if necessary, reduce the limit values they have laid down in accordance with Annex I A.").

[263] Council of the European Communities (1986) COUNCIL DIRECTIVE OF 12 JUNE 1986 ON THE PROTECTION OF THE ENVIRONMENT, AND IN PARTICULAR OF THE SOIL, WHEN SEWAGE SLUDGE IS USED IN AGRICULTURE (86/278/EEC), ANNEX II A, ¶ 3 ("Subject to the provisions of paragraph 4 , analysis should cover the following parameters:— dry matter, organic matter, — pH, — nitrogen and phosphorus, — cadmium, copper, nickel, lead, zinc, mercury, chromium.").

[264] Council of the European Communities (1991) COUNCIL DIRECTIVE OF 12 DECEMBER 1991 CONCERNING THE PROTECTION OF WATERS AGAINST POLLUTION CAUSED BY NITRATES FROM AGRICULTURAL SOURCES (91/676/EEC), Art. 1 ("This Directive has the objective of: — reducing water pollution caused or induced by nitrates from agricultural sources and — preventing further such pollution.").

[265] Council of the European Communities (1991). COUNCIL DIRECTIVE OF 12 DECEMBER 1991 CONCERNING THE PROTECTION OF WATERS AGAINST POLLUTION CAUSED BY NITRATES FROM AGRICULTURAL SOURCES (91/676/EEC), Art. 3, ¶¶ 1, ("1 . Waters affected by pollution and waters which could be affected by pollution if action pursuant Article 5 is not taken shall be identified by the Member States in accordance with the criteria set out in Annex I." Art. 4, ¶¶ 2, ("2. Member States shall, within a two-year period following the notification of this Directive, designate as vulnerable zones all known areas of land in their territories which drain into the waters identified according to paragraph 1 and which contribute to pollution. They shall notify the Commission of this initial designation within six months.").

[266] Council of the European Communities (1991) COUNCIL DIRECTIVE OF 12 DECEMBER 1991 CONCERNING THE PROTECTION OF WATERS AGAINST POLLUTION CAUSED BY NITRATES FROM AGRICULTURAL SOURCES (91/676/EEC), Annex III, ¶¶ 1.1, 1.3 (" The measures shall include rules relating to: 1. periods when the land application of certain types of fertilizer is prohibited; … 3. limitation of the land application of fertilizers, consistent with good agricultural practice and taking into account the characteristics of the vulnerable zone concerned ….").

[267] European Commission (2017) *EU ETS Handbook*, 20 ("In phase 1 the EU ETS covered CO_2 emissions. Voluntary inclusion of N_2O emissions was allowed from phase 2 at the discretion of EU Member States. Starting from phase 3 certain N_2O and PFC emissions were also covered. The EU ETS in phase 3 covers CO_2 emissions, N_2O emissions from all nitric, adipic and glyoxylic acid production and PFC emissions from aluminium production.").

[268] European Commission (2017) *EU ETS Handbook*, 26 ("In phase 3, full auctioning of allowances will be required for the power sector, while for industry and heating sectors, allowances will be allocated for free based on ambitious greenhouse gas performance benchmarks. For the third trading period (2013 – 2020), free allocation is implemented by applying new EU-wide, fully harmonised, allocation rules. Member States are still required to prepare an "allocation plan", known as the National Implementation Measures (NIMs) document which contains all of the detailed information about the allocations planned for each installation in the country. Member States remain responsible for data collection and final allocation.").

[269] European Parliament (2022) *EU carbon border adjustment mechanism Implications for climate and competitiveness*, 2 ("In July 2021, the EU announced a set of proposals (also known as the 'Fit for 55' package) that would deliver the Green Deal and help achieve the emissions reduction target while creating new social and economic opportunities. As part of this package, a carbon border adjustment mechanism (CBAM) would be gradually introduced for certain imports from third countries. The aim of the CBAM is to equalise the carbon price between domestic and foreign products, thereby limiting carbon leakage; the measure could also encourage partner countries to adopt carbon pricing that tests the prediction of a Brussels effect.").

[270] European Commission (14 July 2021) *Annexes to the Regulation of the European Parliament and of the Council establishing a carbon border adjustment mechanism*, SWD(2021) 647 final, 1 (*see* table on fertilisers).

[271] European Parliament (2022) *EU carbon border adjustment mechanism Implications for climate and competitiveness*, 2 ("In the transitional phase, as of 2023, importers in these sectors will have to report their embedded GHG emissions of CO_2 and, where relevant, nitrous oxide (N_2O) and perfluorocarbons (PFCs). They will not yet have to pay the financial adjustments.").

[272] European Commission. *Carbon Border Adjustment Mechanism* (*last visited* 27 August 2024) (*" If importers can prove that a* ***carbon price has already been paid*** *during the production of the imported goods, the corresponding amount* ***can be deducted."***).

[273] European Commission. *Carbon Border Adjustment Mechanism* (*last visited* 27 August 2024) ("On 1 October 2023, the CBAM entered into application in its transitional phase, with the first reporting period for importers ending 31 January 2024. The gradual phasing in of CBAM allows for a careful, predictable and proportionate transition for EU and non-EU businesses, as well as for public authorities.
The CBAM will **initially apply to imports of certain goods and selected precursors** whose production is carbon intensive and at most significant risk of carbon leakage: **cement, iron and steel, aluminium, fertilisers, electricity and hydrogen**. With this enlarged scope, CBAM will eventually – when fully phased in – capture more than 50% of the emissions in ETS covered sectors..")(emphasis in original).

[274] European Commission. *Carbon Border Adjustment Mechanism* (*last visited* 27 August 2024) ("During this period, importers of goods in the scope of the new rules will only have to report greenhouse gas emissions (GHG) embedded in their imports (direct and indirect emissions), without the need to buy and surrender certificates. Indirect emissions will be covered in the scope after the transitional period for some sectors (cement and fertilisers), on the basis of a defined methodology outlined in the Implementing Regulation published on 17 August 2023 and its accompanying guidance.").

[275] van Halm I. (16 August 2022) *The Dutch nitrogen crisis shows what happens when policymakers fail to step up*, ENERGY MONITOR ("The Netherlands has the second highest nitrogen balance (or surplus) in Europe. On average, European countries had 68 kilograms of nitrogen per hectare between 2010 and 2015. The Netherlands had an average gross nitrogen balance of more than two times as much.").

[276] Stokstad E. (4 December 2019) *Nitrogen crisis from jam-packed livestock operations has 'paralyzed' Dutch economy*, SCIENCE ("In 118 of 162 Dutch nature reserves, nitrogen deposits now exceed ecological risk thresholds by an average of 50%. In dunes, bogs, and heathlands, home to species adapted to a lack of nitrogen, plant diversity has decreased as nitrogen-loving grasses, shrubs, and trees move in. Heathlands are turning green-gray as invasive grasses overwhelm the purple heather and yellows and blues of small herbaceous flowering plants, says Eva Remke, an ecologist at B-WARE Research Centre in Nijmegen. 'The grasses will win, and the herbs will lose.' These losses cascade through the ecosystem, contributing to the decline of insect and bird diversity, she says.").

[277] Stokstad E. (4 December 2019) *Nitrogen crisis from jam-packed livestock operations has 'paralyzed' Dutch economy*, SCIENCE ("To control emissions, in 2015 the Netherlands introduced a nitrogen permit system that allows construction if, for example, regional governments reduce nitrogen from other sectors, such as farming. The system relies on a model developed by the Dutch National Institute for Public Health and the Environment (RIVM) to calculate how much nitrogen is emitted by various activities and how much they contribute to pollution in natural areas. The system was not enough to satisfy environmental groups. They sued the Dutch government in 2016, demanding that it deny construction permits for expanded animal operations near two nature reserves. The cases ended up in the Court of Justice of the European Union, which last year ruled against the government and criticized the permit system for not ensuring immediate nitrogen reductions. The Dutch high court implemented the ruling in May, halting all permit applications. It said the government needed to come up with a better system and a long-term plan to reduce nitrogen emissions.").

[278] van der Hoek M. (21 June 2022) *Government Presents National Program to Reduce Nitrogen Greenhouse Gas Emissions in Rural Areas*, 2 ("On June 10, 2022, Minister Van der Wal delivered a much-anticipated presentation on the government's quantitative and qualitative objectives for Dutch agriculture in order to reduce nitrogen GHG emissions, which was followed by a press conference led by Prime Minister, Mark Rutte.").

[279] van der Hoek M. (21 June 2022) *Government Presents National Program to Reduce Nitrogen Greenhouse Gas Emissions in Rural Areas*, 2 ("To reach the goal, the government has indicated a 40 percent reduction in nitrogen GHG emissions is needed (with the goal of a 39 kiloton {kton} reduction of ammonia {NH3} emissions) within the agricultural sector. This National Program has been transformed into detailed area-specific emission reduction objectives (see Figure 1 below) to be addressed at the Provincial level.").

[280] Reuters (22 June 2022) *Dutch farmers protest plan to curb nitrogen pollution*, REUTERS: ENVIRONMENT ("Farmers argue the targets are poorly conceived and unfair. They are expected to lead to a 30% reduction in the number of Dutch livestock, with effects more concentrated in agricultural areas bordering nature preserves. 'These reductions are so severe that those rural communities will be totally devastated economically, and that's the reason our farmers are going to Stroe today' said Sander van Diepen, a spokesperson for agricultural organization LTO."); Koc C. (28 June 2022) *Dutch Farmers Bring Cows to Parliament to Protest Nitrogen Cuts*, BNN BLOOMBERG ("Angry Dutch farmers brought their cows to parliament, threatening to slaughter them in protest of the government's nitrogen reduction targets. 'If the nitrogen measures are adopted, one of these two ladies will not go home, but will receive a one-way ticket to the slaughterhouse,' Dutch news agency ANP cited farmer Koos Cromwijk as saying in front of parliament.").

[281] van der Hoek M. (21 June 2022) *Government Presents National Program to Reduce Nitrogen Greenhouse Gas Emissions in Rural Areas*, 2 ("In 2021 the newly installed Dutch government stressed the need for a new approach to address nitrogen emissions for agriculture and nature. Until 2035, the Dutch government provided €24.3 billion ($25.3 billion) in funding to address issues related to nitrogen GHG, as well as water quality, soils, climate, and biodiversity. These funds were added to the €7 billion ($7.3 billion) which had already been earmarked."); Diedrik B. (26 November 2022) *Netherlands to Buy Out Farmers Amid Pushback Over Nitrogen Goals*, BNN BLOOMBERG ("The Netherlands laid out plans to buy out hundreds of farms near nature reserves, an attempt to quell the fury of Dutch farmers over its goal of halving nitrogen emissions by 2030. The government will acquire large nitrogen emitters as part of a voluntary and one-time offer, said Nitrogen Minister Christianne van der Wal-Zeggelink in a letter to the parliament in the Hague. The cabinet has set aside €24.3 billion to fund the transition.").

[282] The White House (23 July 2024) *FACT SHEET: Biden-Harris Administration Announces New Actions to Detect and Reduce Climate Super Pollutants*, Statements and Releases ("Leading U.S. companies showcased new actions that, by early 2025, will reduce overall U.S. industrial emissions of nitrous oxide by over 50% since 2020.").

[283] The White House (23 July 2024) *FACT SHEET: Biden-Harris Administration Announces New Actions to Detect and Reduce Climate Super Pollutants*, Statements and Releases ("Ascend Performance Materials, the largest producer of adipic acid in the United States, announced the installation of an additional thermal reduction unit that has virtually eliminated N_2O emissions at their Florida facility.").

[284] The White House (23 July 2024) *FACT SHEET: Biden-Harris Administration Announces New Actions to Detect and Reduce Climate Super Pollutants*, Statements and Releases ("ClimeCo, a global sustainability company and the largest developer of industrial N_2O abatement projects in the United States, announced three new emissions reduction projects that will come online by early 2025 and reduce nitrous oxide emissions at the three facilities by approximately 95%.").

[285] Climate Advisors, Institute for Governance & Sustainable Development and The Asia Society (31 July 2024) *US-China Cooperation on Reducing Industrial N_2O Emissions* ("Bill Flederbach, President and CEO of ClimeCo, an N_2O carbon market project developer, announced his company's commitment to expand beyond its US-based projects to

launch four new adipic projects in China with the potential to prevent the release of N_2O emissions equivalent to 60 million tons of carbon dioxide (CO_2).").

[286] The White House (17 June 2022) *FACT SHEET: President Biden to Galvanize Global Action to Strengthen Energy-Security and Tackle the Climate Crisis through the Major Economies Forum on Energy and Climate*, Statements and Releases.

[287] The White House (17 June 2022) *FACT SHEET: President Biden to Galvanize Global Action to Strengthen Energy-Security and Tackle the Climate Crisis through the Major Economies Forum on Energy and Climate*, Statements and Releases ("A 10 percent reduction in global fertilizer loss and waste would free up more than the total amount of mineral fertilizer used by all African countries.").

[288] The White House (17 June 2022) *FACT SHEET: President Biden to Galvanize Global Action to Strengthen Energy-Security and Tackle the Climate Crisis through the Major Economies Forum on Energy and Climate*, Statements and Releases ("In addition, nitrogen fertilizer production consumes up to 4 percent of global natural gas supply; increasing fertilizer efficiency in the short term and transitioning to more affordable alternatives in the medium term will reduce natural gas dependence. Steps to increase the adoption of innovative, alternative, and efficient fertilizer and cropping practices will alleviate pressure on fertilizer and natural gas supplies, increase fertilizer availability, lower nitrous oxide emissions, and reduce food insecurity globally.").

[289] U.S. Department of State (12 November 2022) *Global Fertilizer Challenge Raises $135 million for Fertilizer Efficiency and Soil Health Measures to Combat Food Insecurity*, Press Release ("Deputy Special Envoy for Climate Richard Duke and high-level partners from the United States, European Commission, Norway, Germany, and the Netherlands announced a total of $135 million in new funding for fertilizer efficiency and soil health programs to combat fertilizer shortages and food insecurity. ").

[290] The White House (17 June 2022) *FACT SHEET: President Biden to Galvanize Global Action to Strengthen Energy-Security and Tackle the Climate Crisis through the Major Economies Forum on Energy and Climate*, Statements and Releases ("In recent months, as part of a continuing effort to add resilience to the agriculture and food supply chains, the United States has established a $500 million program to support innovative and sustainable U.S. fertilizer production and has strengthened support to farmers for the use of precision agriculture and other techniques to improve fertilizer use efficiency.").

[291] Exec. Order No. 13990, 86 FED. REG. 7037 (January 25, 2021) ("There is hereby established an Interagency Working Group on the Social Cost of Greenhouse Gases (the 'Working Group'). The Chair of the Council of Economic Advisers, Director of OMB, and Director of the Office of Science and Technology Policy shall serve as Co-Chairs of the Working Group.").

[292] *See* Interagency Working Group on Social Cost of Greenhouse Gases, United States Government (February 2021) TECHNICAL SUPPORT DOCUMENT: SOCIAL COST OF CARBON, METHANE, AND NITROUS OXIDE: INTERIM ESTIMATES UNDER EXECUTIVE ORDER 13990, 25 (Table 3: Social Cost of N_2O, 2020 – 2050 *showing* the social cost of N_2O at the discount rates of 5%, 3%, and 2.5% in five year increments from 2020 to 2050).

[293] U.S. EPA (2023) EPA REPORT ON THE SOCIAL COST OF GREENHOUSE GASES: ESTIMATES INCORPORATING RECENT SCIENTIFIC ADVANCES, 9 ("The EPA applied the IWG's interim SC-GHG estimates in analyses published following the release of the February 2021 TSD (see, e.g., EPA (2021b, 2021c)).").

[294] The People's Republic of China (29 December 2023) *Third Biennial Update Report on Climate Change*, 9 ("China's N_2O emissions in 2018 were 1.915 Mt, of which 0.411 Mt were from Energy, accounting for 21.5%; 0.441 Mt were from Industrial Processes, accounting for 23.0%; 0.943 Mt were from Agriculture, accounting for 49.2%; 1 kt were from LULUCF, accounting for less than 0.1%; 0.119 Mt were from Waste, accounting for 6.2%.").

[295] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYSTEMS SCIENCE DATA 16: 2543–2604, 2571 ("According to the BU [bottom-up] results, China's total N2O emissions increased from 0.76 Tg N yr^{-1} in 1980 to 1.38 Tg N yr^{-1} in 2020. … The BU and TD [top-down] approaches gave consistent estimates of China's total N_2O emissions in the 2010s, with values of 1.41 (0.82–2.23) and 1.33 (1.06–1.60) Tg N yr^{-1} for the BU and TD approaches (Fig. 15), respectively. According to the BU results, natural sources only contributed 21 % of total emissions (0.29, 0.20–0.51 Tg N yr^{-1}) during this period. Nitrogen additions in agriculture were the dominant source of N_2O emissions, contributing 48 % of the total emissions (0.68, 0.48–1.03 Tg N yr^{-1}).").

[296] Liang M., Zhou Z., Ren P., Xiao H., Xu-Ri, Hu Z., Piao S., Tian H., Tong Q., Zhou F., Wei J., & Yuan W. (2024) *Four decades of full-scale nitrous oxide emission inventory in China*, NAT'L SCI. REV. 11:nwad285, 2 ("The growing rate of N fertilizer applications has started to slow down and a decelerating trend was observed after 2016, owing to the release of the *Zero Growth in Fertilizer Plan* [12]."); Ji Y., Liu H., & Shi Y. (2020) *Will China's fertilizer use continue to decline? Evidence from LMDI analysis based on crops, regions and fertilizer types*, PLOS ONE 15:1–19, 2 ("In 2015, the Chinese government promulgated the Action Plan for the Zero Increase of FU, which proposed a goal of 'zero growth of FU, the establishment of a scientific fertilizer management technology system, and the improvement of the scientific FU level'".).

[297] Shuqin J. & Zhou F. (2018) *Zero Growth of Chemical Fertilizer and Pesticide Use: China's Objectives, Progress and Challenges*, J. OF RESOURCES & ECOLOGY 9:50–58, 52 ("The key tasks to achieve zero growth of chemical fertilizer use are the 'four promotions and one improvement': (1) Promote soil testing and formulated fertilization[1]. On the basis of past experiences, soil testing and formulated fertilization shall be promoted on a larger scale and higher level by adopting an innovative approach to implementation. (2) Promote improved fertilization methods. New types of business entities, including large-scale grain farms, family farms, cooperatives, etc., will play exemplary roles in order to strengthen technical training and guidance services, popularize advanced and applicable techniques, and promote improved fertilization methods. (3) Promote application of new fertilizers and new techniques. Scientific research, education, promotion, and corporate resources will be integrated for joint research based on the needs of agricultural production, with increases in R&D investment and channels to obtain international advanced techniques. (4) Promote the use of organic fertilizers. An effective model for the use of organic fertilizers that is adapted to the needs of modern agriculture development and the characteristics of China's agricultural system will be identified and farmers will be encouraged and given support to increase organic fertilizer use. (5) Improve cropland quality. The development of high standard cropland will be accelerated, and actions to protect and enhance cropland quality will be implemented to improve soil fertility. By 2020, the fertility of cropland will rise by at least 0.5% in terms of grade, the organic matter content of soil will increase by 0.2%, and acidification, salinization, pollution and other problems with cropland shall be effectively controlled.").

[298] Zhang Z., Hou L., Qian Y. & Wan X. (2022) *Effect of Zero Growth of Fertilizer Action on Ecological Efficiency of Grain Production in China under the Background of Carbon Emission Reduction*, SUSTAINABILITY 14:15362, 2 ("According to the data of 'China Rural Statistical Yearbook' and using relevant research methods [4] to calculate, the amount of fertilizer applied in China's grain production has decreased from 40.405 million tons in 2015 to 35.852 million tons in 2020, a decrease of 11.2%, as shown in Figure 1a. Non-point source pollution of fertilizers and carbon emissions of fertilizers in the process of grain production also showed a gradual decline, as shown in Figure 1b, c. However, grain output in China gradually increased and maintained a high level, increasing by 7.7% from 621.438 million tons in 2015 to 669.491 million tons in 2020, as shown in Figure 1d.").

[299] Implementation Plan for Emission Reduction and Carbon Sequestration in Agriculture Sector and Rural Area [农业农村减排固碳实施方案] (promulgated by the Ministry of Agriculture and Rural Affairs and the National Development and Reform Commission, Jun. 30, 2022; effective Jun. 30, 2022) (hyperlink to original Chinese text).

[300] Central People's Government of China (17 January 2021) *Efficiency Rate over 40%: Target Achieved for Action on Zero Growth of Fertilizer and Pesticide Use* [利用率过 40%：化肥农药使用量零增长行动实现目标] (hyperlink to original Chinese text).

[301] Opinions on Strengthening the Battle for Pollution Prevention and Control [关于深入打好污染防治攻坚战的意见] (promulgated by the Central Committee of the Chinese Communist Party and the State Council, Nov. 2, 2021; effective Nov. 2, 2021) (hyperlink to original Chinese text).

[302] Ministry of Agriculture and Rural Affairs of China (28 July 2023) *Response to Recommendation No. 6904 from the First Session of the Fourteenth National People's Congress* [对十四届全国人大一次会议第 6904 号建议的答复] (hyperlink to original Chinese text).

[303] Opinions on Strengthening the Battle for Pollution Prevention and Control [关于深入打好污染防治攻坚战的意见] (promulgated by the Central Committee of the Chinese Communist Party and the State Council, Nov. 2, 2021; effective Nov. 2, 2021) (hyperlink to original Chinese text).

[304] Methane Emissions Control Action Plan [甲烷排放控制行动方案] (promulgated by the Ministry of Ecology and Environment et al., Nov. 7, 2023; effective Nov. 7, 2023) (hyperlink to original Chinese text) (IGSD's annotated, English reference translation of the China Methane Action Plan is available here.).

[305] Guiding Opinions for Promoting the Construction of Ecological Farms [推进生态农场建设的指导意见] (promulgated by the General Office of the Ministry of Agriculture and Rural Affairs, Feb. 9, 2022; effective Feb. 9, 2022) (hyperlink to original Chinese text).

[306] Cui X., Shang Z., Xia L., Xu R., Adalibieke W., Zhan X., Smith P., & Zhou F. (2022) *Deceleration of Cropland-N_2O Emissions in China and Future Mitigation Potentials*, ENVTL. SCIENCE & TECHNOLOGY 56:4665–4675. 4665 ("About 63% of N_2O emissions could be reduced in 2050, primarily in the North China Plain and Northeast China Plain; 83% of which is from the production of maize (33%), vegetables (27%), and fruits (23%). The deceleration of N_2O emissions highlights that policy interventions and agronomy practices (i.e., optimizing N rate and sowing structure) are potential pathways for further ambitious N_2O mitigation in China and other developing countries.").

[307] Cui X., Shang Z., Xia L., Xu R., Adalibieke W., Zhan X., Smith P., & Zhou F. (2022) *Deceleration of Cropland-N_2O Emissions in China and Future Mitigation Potentials*, ENVTL. SCIENCE & TECHNOLOGY 56:4665–4675, 4672 ("Therefore, possible measures to mitigate N_2O emissions from vegetables and fruits mainly in the North China Plain, include reducing N fertilizer application rate, applying high-efficiency fertilizers [45] and optimizing irrigation.[46]")

[308] Cui, X., Shang Z., Xia L., Xu R., Adalibieke W., Zhan X., Smith P., & Zhou F. (2022) *Deceleration of Cropland-N_2O Emissions in China and Future Mitigation Potentials*, ENVTL. SCIENCE & TECHNOLOGY 56:4665–4675, 4672 ("According to mitigation potentials under different scenarios by crop, it can be found that optimizing N_{rate} and diet structure for maize has the greatest mitigation potentials (Figure 4b). Therefore, for maize mainly planted in the North China Plain and Northeast China Plain, reducing N_{rate} input, and sowing area are effective pathways for mitigation. The latter can be achieved by national or interprovincial collaborations and food trade,[47] that is, maize may be planted in regions where EF is relatively lower instead of Northeast with higher EF, meanwhile, maintaining yields.").

[309] Liang M., Zhou Z., Ren P., Xiao H., Xu-Ri, Hu Z., Piao S., Tian H., Tong Q., Zhou F., Wei J., & Yuan W. (2024) *Four decades of full-scale nitrous oxide emission inventory in China*, NAT'L SCI. REV. 11:nwad285, 4 ("For the decades of 2000–2010 and 2010–2020, the total N_2O emissions kept increasing by 31.5% and 23.1%, respectively, while energy and industry exceeded agriculture and became the fastest- increasing N_2O sources in China.").

[310] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NATURE CLIMATE CHANGE 13:599–601, 600 ("Of the 21 adipic acid plants worldwide, 11 are in China, making it the largest emitter of N_2O (Table 2)."; *see also* Table 2 showing that the total N_2O emissions from countries with adipic acid manufacturing amounts to 307 ktN_2O yr^{-1} while China's N_2O emissions from adipic acid manufacturing amounts to 288 ktN_2O yr^{-1}).

[311] Gu B., Xu X., Zhang X., Zhang S., Winiwarter W., Wang C., Reis S., & Xu J. (2023) *Synergies of reducing greenhouse gases and atmospheric nitrogen pollutants in China*, NATURE PORTFOLIO, pre-print, 5 ("Further, we estimated and compared the costs and benefits of GHG-ANP co-reduction under different scenarios in China (Fig. 5). All three co-control scenarios demonstrate that the total social benefits of collaborative emissions reduction outweigh the implementation costs significantly, occurring in most provinces of China… The SSP1-26-strong policy scenario incurs the most substantial abatement expenses (~240 billion USD yr-1) to attain the highest synergistic abatement potential and overall societal gains at 1964 billion USD in 2050 (Fig. 5a).").

[312] U.S. EPA (2019) *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation: 2015–2050*, 29 (China and the United States can reach 61% and 49% of their national abatement potential at break-even prices below \$10/tCO_2e.").

[313] People's Republic of China (2022) *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, Unofficial Translation, 39.

[314] Opinions on Comprehensively Promoting the Construction of a Beautiful China [关于全面推进美丽中国建设的意见] (promulgated by the Central Committee of the Chinese Communist Party and the State Council, Dec. 27, 2023; effective Dec. 27, 2023) (hyperlink to original Chinese text).

[315] IGSD (12 September 2024) *China Explores Opportunities to Address Nitrous Oxide Emissions*.

[316] U.S. Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis*.

[317] The White House (23 July 2024) *FACT SHEET: Biden-Harris Administration Announces New Actions to Detect and Reduce Climate Super Pollutants*, Statements and Releases ("Leading U.S. companies showcased new actions that, by early 2025, will reduce overall U.S. industrial emissions of nitrous oxide by over 50% since 2020.").

[318] Climate Advisors, Institute for Governance & Sustainable Development and The Asia Society (31 July 2024) *US-China Cooperation on Reducing Industrial N_2O Emissions* ("Bill Flederbach, President and CEO of ClimeCo, an N_2O carbon market project developer, announced his company's commitment to expand beyond its US-based projects to launch four new adipic projects in China with the potential to prevent the release of N_2O emissions equivalent to 60 million tons of carbon dioxide (CO_2).").

[319] He Waka Eke Noa (October 2020) *5-Year Programme Overview* ("By 2025 all farmers and growers are: • including climate change mitigation and adaptation in their farm business and environment plans. • calculating their net greenhouse gas emissions and being incentivised to take action on climate change through an appropriate pricing mechanism for emissions.").

[320] Corlett E. (11 October 2022) *New Zealand farmers may pay for greenhouse gas emissions under world-first plans*, THE GUARDIAN ("In a world-first, New Zealand appears set to introduce a scheme that will require farmers to pay for their agricultural greenhouse gas emissions, including the methane belched out by cows and nitrous oxide emitted through livestock urine.").

[321] Corlett E. (11 October 2022) *New Zealand farmers may pay for greenhouse gas emissions under world-first plans*, THE GUARDIAN ("Under the proposed plan, by 2025, farmers who meet the threshold for herd size and fertiliser use, will be required to pay a levy the government will set every one to three years, on advice from the Climate Change Commission and farmers. The price will be influenced by the country's progress towards meeting its international promise to cut methane by 10% by 2030, down from 2017 levels. It comes alongside a net-zero emissions target for 2050.").

[322] Corlett E. (11 October 2022) *New Zealand farmers may pay for greenhouse gas emissions under world-first plans*, THE GUARDIAN ("All revenue from the levy will go towards new technology, research and incentive payments to farmers who adopt climate-friendly practices.").

[323]Deutsche Welle (20 October 2022) *New Zealand farmers protest plan to tax cow burps* ("The protesting farmers took to the streets with convoys of tractors and farmyard vehicles. They were demanding the government drop the plan, which they said would harm their livelihood and make food more expensive.").

[324] Craymer L. (18 August 2023) *New Zealand pushes back start date for price on farm emissions*, REUTERS ("New Zealand farmers will have until the end of 2025 before they have to pay for methane produced by sheep and cattle, after the Labour government on Friday pushed back its plans to price agricultural emissions of greenhouse gases. … Agriculture Minister Damien O'Connor said pricing of such emissions would start in the fourth-quarter of 2025, back from a previously planned start in the first quarter to give farmers more time to adjust.").

[325] Lupescu M. (12 March 2021) *Canada Proposes Federal Carbon Offset System*, USDA FOREIGN AGRICULTURAL SERVICE (*last accessed on* 27 August 2024) ("On March 5, 2021, the federal government announced draft regulations to establish the Federal Greenhouse Gas Offset System. These regulations – open for a 60-day public consultation through May 5, 2021 – will enable the development of federal offset protocols allowing participants in a protocol, including farmers, to generate carbon offset credits tradable via CATS to industrial GHG emitters.").

[326] Government of Canada (06 May 2024) *Improved forest management on private land (protocol version 1.0)* ("The *Improved Forest Management on Private Land* federal offset protocol is intended for use by a proponent undertaking a project to carry out forest management activities on managed forestlands that go beyond a business-as-usual management scenario in order to generate greenhouse gas (GHG) emission reductions and removals (GHG reductions) for which federal offset credits may be issued under the Canadian Greenhouse Gas Offset Credit System Regulations (Regulations).").

[327] Lupescu M. (12 March 2021) *Canada Proposes Federal Carbon Offset System*, USDA Foreign Agricultural Service (*last accessed on* 27 August 2024) ("Finally, and subject to 'the results of further analysis and pilot projects,' additional agriculture-related protocols may be considered for development, such as:
- Avoided Conversion of Grasslands
- Reduced Nitrogen Oxide Emissions from Agriculture Fertilizer, and
- Livestock Manure Management.").

[328] Environment and Climate Change Canada (2021) *A Healthy Environment and a Healthy Economy*, 45 ("To help farmers and food businesses continue to develop and implement clean practices that reduce greenhouse gas emissions and ensure agriculture remains a leading part of the solution to climate change, this plan will:
- Set a national emission reduction target of 30% below 2020 levels from fertilizers and work with fertilizer manufacturers, farmers, provinces and territories, to develop an approach to meet it. Direct emissions associated with synthetic nitrogen fertilizer application have increased by approximately 60% since 2005 and these emissions are projected to keep increasing. Improving how fertilizers are used through better products and practices will save farmers money and time, and help protect Canada's land and water.").

[329] Agriculture and Agri-Food Canada (2023). *Agriculture and Agri-Food Canada Departmental Plan*, 3 ("The Sustainable Canadian Agricultural Partnership (Sustainable CAP) is the new five-year (2023 to 2028) agricultural policy framework that comes into effect as of April 1, 2023. This new framework will provide a total of $3.5 billion in federal, provincial and territorial funding for the agriculture and agri-food sector, an increase of $500 million in funding available for cost-shared programming compared to its predecessor, the Canadian Agricultural Partnership2 (2018 to 2023). Agriculture is a shared responsibility in Canada between federal, provincial, and territorial (FPT) governments. The Sustainable CAP will set the strategic direction for coordinated FPT programs and activities, while positioning the sector for continued success as a world leader in environmentally, economically, and socially sustainable agriculture. It will enable an innovative, productive, and internationally competitive sector that can continue to meet the expectations of consumers among a growing global population, at a time when rising costs and global food security are significant concerns..").

[330] Agriculture and Agri-Food Canada (2023). *Agriculture and Agri-Food Canada Departmental Plan*, 4 ("Under the Sustainable CAP, the Department will work to tackle climate change and environmental protection, including by seeking to reduce greenhouse gas emissions by three to five megatonnes over the implementation period of the framework.").

[331] Fertilizer Canada. *Sustainable Farming is the Future (last visited* on 27 August 2024).

[332] Climate & Clean Air Coalition. *About* (*last accessed* 26 August 2024).

[333] Climate and Clean Air Coalition (09 December 2023) *Ministers Unite for Immediate Action on Climate and Clean Air, Urging Bold Financing and Swift Measures on Non-CO_2 Super Pollutant Greenhouse Gases*, News and Announcements ("The Coalition also announced the initiation of a landmark assessment on nitrous oxide (N_2O) to be delivered in advance of COP29, which will expose impacts of the often-overlooked greenhouse gas. This proactive approach aims to ensure that no opportunities are missed in the pursuit of a 1.5 degrees Celsius future. A global assessment on the cost of inaction on short-lived climate pollutants and an assessment on the integrated agriculture and food systems will be prepared in advance of COP30.").

[334] Patel M. (31 July 2024) *US-China Cooperation on Reducing Industrial N_2O Emissions*, CLIMATE ADVISERS ("Kanter indicated that there will be a soft launch of the forthcoming CCAC N_2O assessment during New York Climate Week (NYCW) in September, ahead of the full, official launch during the Meeting of the Parties to the Montreal Protocol (MOP) in late October.").

[335] Climate and Clean Air Coalition. *Our Approach* (*last accessed* 26 August 2024) ("The Climate and Clean Air Coalition supports action to reduce short-lived climate pollutants in over 70 countries through our project funding and the individual actions of our partners. We aim to connect ambitious agenda setting with targeted mitigation action within countries and sectors. Robust science and analysis underpin our efforts. Our work is focused on five key areas.").

[336] Nitric Acid Climate Action Group (NACAG), *Introducing the Nitric Acid Climate Action Group* (*last visited* 26 January 2023) ("NACAG aims to promote the installation of effective nitrous oxide (N_2O) abatement technology in all nitric acid and caprolactam plants worldwide. To this end, NACAG offers technical, political and financial assistance to eligible partner countries. The initiative offers governments and plant operators guidance and information on technological and regulatory aspects of N_2O abatement. Furthermore, NACAG provides financial support for the procurement and installation of emission abatement technologies to eligible countries entitled for Official Development Assistance (ODA). This financial support is subject to the condition that the partner countries take full responsibility for the reduction activities – for example within the framework of their Nationally Determined Contributions (NDCs) in accordance with the Paris Agreement. The commitment of partner countries to reduce emissions ensures the sustainability of initiated activities and the long-term transformation of the sector.").

[337] NACAG, *Financial Support* (*last accessed* 27 August 2024) ("The initiative provides financial support to individual nitric acid plant operators for their abatement activities on the condition that the country in which the plant is located is committed to sustaining the emission abatement in the future. This commitment should take the form of a formal Statement of Undertaking signed by the government. In the Statement of Undertaking, the government commits to ensuring that all nitric acid or caprolactam production facilities in the country are equipped with state-of-the-art technology to abate N_2O emissions from their production cycles on a long-term basis. NACAG is supporting new abatement projects by covering up to 100% of the costs associated with the purchase and installation of the abatement and monitoring technology. Nitric acid or caprolactam plant operators from eligible countries can apply for financial support, which effectively takes the form of grants. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH is the executive development cooperation agency of this funding stream and acts as the grant managing and contracting authority.").

[338] NACAG, *Partner Countries* (*last accessed* 27 August 2024) ("Statement of Undertaking (SoU) and thereby expressed their support for NACAG's objective. The initiative is continuously open for new partners to join."; *see* list of Partner countries).

[339] UNEP/EA.4/Res.14 (2019) *Resolution Adopted by the United Nations Environment Assembly on 15 March 2019, Sustainable Nitrogen Management*, Nairobi, Kenya.

[340] UNEP/EA.4/Res.14 (2019) *Resolution Adopted by the United Nations Environment Assembly on 15 March 2019, Sustainable Nitrogen Management*, Nairobi, Kenya ("*Recognizing* the multiple pollution threats resulting from anthropogenic reactive nitrogen, with adverse effects on the terrestrial, freshwater and marine environments, and to air pollution and greenhouse gas emissions, while acknowledging the benefits of nitrogen use for food and energy production, … *Realizing* that intersectorally incoherent approaches to the global nitrogen cycle are resulting in unquantified trade-offs between different forms of nitrogen pollution and contributing to barriers to the adoption of policies for cleaner water, cleaner air, climate change mitigation and adaptation, and biodiversity protection . . . Calls on the Executive Director of the United Nations Environment Programme to: (a) *Consider* the options for facilitating improved coordination of policies across the global nitrogen cycle at the national, regional and global levels, including consideration of the case for establishing an intergovernmental mechanism for coordination of nitrogen policies, based primarily on existing networks and platforms, and consideration of the case for developing an integrated nitrogen policy, which could enhance recognition of the need for common action across multiple policy domains; …").

[341] Sutton M. A., *et al.* (2021) *The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond*, One Earth 4:10–14, 12 ("Four options[14,15] were reviewed with member-state representatives during the high-level segment of the INMS-4 meeting at UNEP Nairobi in April 2019: Option 1: the status quo of nitrogen fragmentation across multi-lateral environmental agreements (MEAs). Option 2: leadership on nitrogen under one existing MEA. Option 3: establishment of a new international convention on nitrogen. Option 4: establishment of an inter-convention nitrogen coordination mechanism (INCOM). Government representatives at the INMS-4 meeting gave a clear preference for option 4. Overall, there was a strong encouragement to work with existing MEAs, while some representatives recommended revisiting option 3 in the future. INMS is now following up with member states under a newly formed UNEP Nitrogen Working Group, preparing the basis for establishing INCOM.").

[342] International Nitrogen Management System (INMS), *First e-briefing for the Nitrogen Working Group of the United Nations Environment Programme* (*last accessed on* 27 August 2024) ("On 8th & 9th June 2020, the UNEP-CEH/GEF 'Towards INMS' Project (INMS) hosted the 'First e-briefing for the Nitrogen Working Group of the United Nations Environment Programme'.").

[343] INMS, *First e-briefing for the Nitrogen Working Group of the United Nations Environment Programme* (*last accessed on* 27 August 2024) ("A Task Group has now been established to refine the Terms of Reference for the Inter-convention Nitrogen Co-ordination Mechanism, with a second e-briefing for the UNEP Nitrogen Working Group planned for the Autumn of 2020.").

[344] Hamilton C. (2023) *Options and Modalities for Improved Coordination of Policies Across the Global Nitrogen Cycle*, 14–16, 21, 35–36 ("Option ii: an existing treaty takes the lead. Case Study: The Montreal Protocol[6]"; "The most appropriate form for an intergovernmental coordination mechanism for nitrogen will largely be dictated by the wishes of UN Member States and the functions they wish to assign to such a mechanism.").

[345] United Nations Environment Assembly (20 November 2023) *Progress in the implementation of resolutions 4/14 and 5/2 on sustainable nitrogen management*, UNEP/EA.6/4, ¶ 7, ¶ 8 ("Since its second meeting, the Working Group has made significant progress in identifying action areas for consideration by Member States in the development of national action plans. Recognizing that Member States are at different stages in the development or implementation of their action plans, UNEP invited Member States that wished to develop a national action plan to contact the secretariat4 for support, subject to the availability of resources."; "As an outcome of the third meeting of the Working Group, the Global Partnership on Nutrient Management provided technical support to the Working Group through (a) technical information-sharing webinars5 held between meetings; (b) the organization of informal expert meetings following the third and fourth meetings of the Working Group to allow for technical discussions among focal points in an informal setting; and (c) support to Member States in terms of the sharing of existing information and knowledge for the development of an evidence-based and intersectorally coherent approach to domestic decision-making to promote sustainable nitrogen management.").

[346] Sutton M. A., *et al.* (2021) *The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond*, One Earth 4:10–14, 13 ("The process further accelerated with the launch of the UN Global Campaign on Sustainable Nitrogen Management in Colombo, Sri Lanka, in October 2019.17 The resulting Colombo Declaration agreed on the ambition to halve nitrogen waste by 2030 as part of National Nitrogen Action Plans, while endorsing the UNEP Road Map for Sustainable Nitrogen Management.").

[347] Sutton M. A., *et al.* (2021) *The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond*, One Earth 4:10–14, 13 ("The new global goal is now taking on a life of its own, developing fresh character as it becomes more widely embraced. For example, in May 2020, the European Commission included the goal to 'reduce nutrient pollution by 50% by 2030' in both its Farm to Fork and Biodiversity Strategies. In addition, the CBD is now considering future adoption of a similar target (CBD/WG2020/2/3).").

[348] United Nations Environment Assembly (2 March 2022) *UNEA Resolution 5/2 Sustainable Nitrogen Management*, UNEP/EA.5/Res.2 ("Taking note of the launch of the United Nations Global Campaign on Sustainable Nitrogen Management in October 2019 and the adoption by its signatories of the Colombo Declaration on Sustainable Nitrogen Management on United Nations Day, 24 October 2019, 3. Requests the Executive Director of the United Nations Environment Programme to: … (b) Identify possible modalities for the options being considered for improved coordination of policies across the global nitrogen cycle at the national, regional and global levels, including, among other options, for an intergovernmental coordination mechanism for nitrogen policies, as specified in subparagraph (a) of resolution 4/14;").

[349] INMS (2023) *Discussion Paper on options for facilitating improved coordination of policies across the global nitrogen cycle: implementing United Nations Environment Assembly (UNEA) Resolution 4/14 and UNEA Resolution 5/2 on sustainable nitrogen management*, 5 ("Each of the MEAs, organisations and processes that are relevant to the mandate of any mechanism11 has its own internal decision-making procedures. The creation of a mechanism should not displace these procedures: for example, decisions falling within the remit of each MEA should be taken by the governing body of that MEA, in accordance with its own procedures. However, a useful starting point could be the recognition (where this has not already happened) of UNEA Resolutions 4/14 and 5/2 by the relevant governing bodies and an explicit statement of interest in collective discussions.").

[350] INMS (2023) *Discussion Paper on options for facilitating improved coordination of policies across the global nitrogen cycle: implementing United Nations Environment Assembly (UNEA) Resolution 4/14 and UNEA Resolution 5/2 on sustainable nitrogen management*, 4 ("The mechanism must be designed in such a way that it is capable of

both attracting and receiving funding from appropriate sources; and of channelling or influencing sustainable and adequate funding for sustainable nitrogen management.").

[351] INMS (2023) *Discussion Paper on options for facilitating improved coordination of policies across the global nitrogen cycle: implementing United Nations Environment Assembly (UNEA) Resolution 4/14 and UNEA Resolution 5/2 on sustainable nitrogen management*, 5 ("The question of timing will also need to be considered, in particular regarding the initial 'authorisation' of any mechanism by the MEAs, organisations or processes: at what point it will be necessary to table or propose resolutions or decisions within the various MEAs, organisations or processes and how this can be sequenced to provide the most effective results. At the initial stages of operation, a phased approach could be considered, targeting outcomes from one forum at a time in a chronological order, rather than targeting multiple forums at the same time. However, there are risks inherent in such an approach if insufficient consultation has been carried out or insufficient flexibility built in to adapt.").

[352] Global Partnership on Nutrient Management (GPNM), *About the Global Partnership on Nutrient Management* (*last accessed* 27 August 2024).

[353] GPNM, *GEF-Global Nutrient Cycling (GNC) Project* (*last accessed* 27 August 2024) ("Project title: Global foundations for reducing nutrient enrichment and oxygen depletion from land based pollution, in support of Global Nutrient Cycle. Project Objective: To provide the foundations (including partnerships, information, tools and policy mechanisms) for governments and other stakeholders to initiate comprehensive, effective and sustained programmes addressing nutrient over-enrichment and oxygen depletion from land based pollution of coastal waters in Large Marine Ecosystems.").

[354]INMS, *About* (*last accessed* 27 August 2024).

[355] INMS, *About* (*last accessed* 27 August 2024), Figure titled "Towards INMS Components and Activities, V5 Aug 2022".

[356] International Nitrogen Initiative (INI), *About INI* (*last accessed* 27 August 2024) ("The International Nitrogen Initiative (INI) is an international program, set up in 2003 under sponsorship of the Scientific Committee on Problems of the Environment (SCOPE) and from the International Geosphere-Biosphere Program (IGBP). The key aims of the INI are to optimize nitrogen's beneficial role in sustainable food production, and minimize nitrogen's negative effects on human health and the environment resulting from food and energy production. Steering Committee meetings are held (online) every two months, and are also attended by a SCOPE representative and the former Steering Committee Chair. During meetings centre directors report on the strategies and developments within their region, providing an internationally coordinated approach to achieve the INI aims. Topics of discussion often include:

- Promoting upcoming meetings, publications and projects,
- developing strategies to raise awareness with policy makers, governments, stakeholders and the public of the benefits of improving nitrogen management,
- and coordinating regional efforts to improve nitrogen management globally.").

[357] NDC Partnership. *Mitigation of Climate Change in Agriculture (MICCA) Programme* (*last accessed* 27 August 2024) ("The Mitigation of Climate Change in Agriculture (MICCA) programme strengthens FAO's longstanding work to address climate change in the agriculture, forestry and fisheries sectors and supports countries participating in the climate change negotiation processes within the United Nations Framework Convention on Climate Change.").

[358] NDC Partnership. *Mitigation of Climate Change in Agriculture (MICCA) Programme* (*last accessed* 27 August 2024) ("The MICCA programme generates technical knowledge, working on the ground and with partners to:● monitor and assess greenhouse gas (GHG) emissions and the mitigation potential in agriculture; ● develop the capacity of stakeholders working on national GHG inventories and farmers using CSA practices; ● carry out life cycle assessments to guide decision making; ● give guidance on climate change mitigation & adaptation options, including

for peatlands and organic soils; ● mainstream gender in CSA; facilitate online communities of practice; and run online learning events.”).

[359] Consultative Group for International Agricultural Research Program on Climate Change, Agriculture, and Food Security [CGIAR-CCAFS]. *Our Research Themes* (*last accessed* 27 August 2024).