N2O Hub

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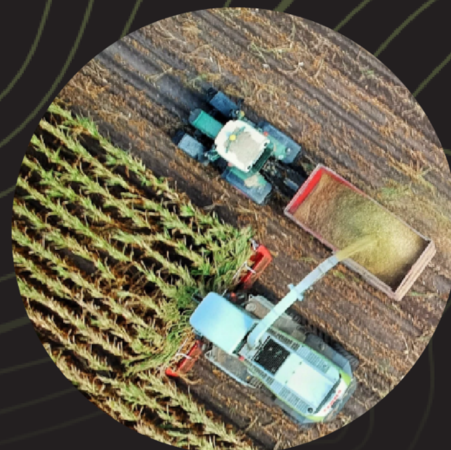

Addressing the *Forgotten* Climate Pollutant

Near-term Opportunities for International Action to Mitigate Emissions of Nitrous Oxide

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About the N_2O Hub

The N_2O Hub is a groundbreaking initiative dedicated to uniting governments, the private sector, civil society, and other key stakeholders to tackle the critical challenge of nitrous oxide (N_2O) emissions. By elevating awareness of the significant harms posed by N_2O emissions and highlighting the opportunities of taking action, the N_2O Hub aims to catalyze new commitments from global leaders to mitigate current and prevent future emissions. The N_2O Hub also focuses on mobilizing finance for the deployment of existing solutions, finance for the research and development of future innovations, and identifying new strategies in partnership with its diverse network of actors. Climate Advisers serves as the secretariat and coordinator of the N_2O Hub, providing organizational support while ensuring that all partners have meaningful opportunities to shape the Hub's strategies and approach. Together, the N_2O Hub aims to create a diverse and inclusive platform that empowers collective action and shared leadership in mitigating N_2O emissions. Learn more at n2oaction.org and follow us on LinkedIn.

About Climate Advisers

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Although it is best known as the “laughing gas” dentists use for sedation, nitrous oxide (N_2O)—a powerful greenhouse gas and ozone-depleting substance mostly emitted by agricultural and industrial activities—is no laughing matter. In fact, in addition to destroying the ozone layer, a kilogram of N_2O traps around 273 times more heat in the atmosphere than the same amount of carbon dioxide on a 100-year timescale.[i]

Unfortunately, nitrous oxide emissions are not only rising but rising faster than in the worst-case emissions scenarios explored by the Intergovernmental Panel on Climate Change (IPCC).[ii] If emissions continue on their current trajectory, there will be no viable path to achieving the Paris Agreement’s goal of limiting warming to 1.5°C.[iii] In addition, much of the world’s population could be exposed to the highest levels of ultraviolet radiation seen since ozone levels were at their lowest.[iv]

This brief provides an introduction to nitrous oxide for climate advocates and policymakers. Section 1 explains why reducing emissions is important, and section 2 covers major emissions sources. Section 3 focuses on key mitigation strategies and challenges to implementing them. Section 4 then summarizes the current state of efforts to address N_2O emissions, including relevant recent efforts by and attention from governments, philanthropy, and NGOs. Finally, section 5 lays out next steps for the international community.

1. Why N_2O Mitigation Matters

Reducing emissions of nitrous oxide is important to achieve internationally agreed climate goals, prevent further damage to and allow for a full recovery of the ozone layer, and improve human health and biodiversity outcomes.

Relevance for climate goals. Nitrous oxide is responsible for about 0.1 degrees C of total warming since pre-industrial times, more than any other greenhouse gas except for carbon dioxide and methane.[v] Moreover, as noted above, nitrous oxide emissions are currently headed in the wrong direction, rising faster than in even the most pessimistic emissions scenarios explored by the IPCC, as shown in Figure 1 below. These scenarios—Representative Concentration Pathway (RCP) 8.5 and Shared Socioeconomic Pathways (SSPs) 3-7.0 and 5-8.5—are associated with around 4 degrees Celsius of total warming by

2100.[vi] One recent analysis found that, if all greenhouse gases are reduced in equal proportion, limiting warming to 1.5, 1.7, or 2 degrees Celsius above pre-industrial levels requires reducing N_2O emissions by about 22%, 18%, and 11% from 2020 levels by 2050 (respectively).[vii] Since the goal agreed to by parties in Paris at COP21 was to hold warming to warming to "well below" 2 degrees, this means that achieving Paris goals will require reducing emissions by at least 11%.

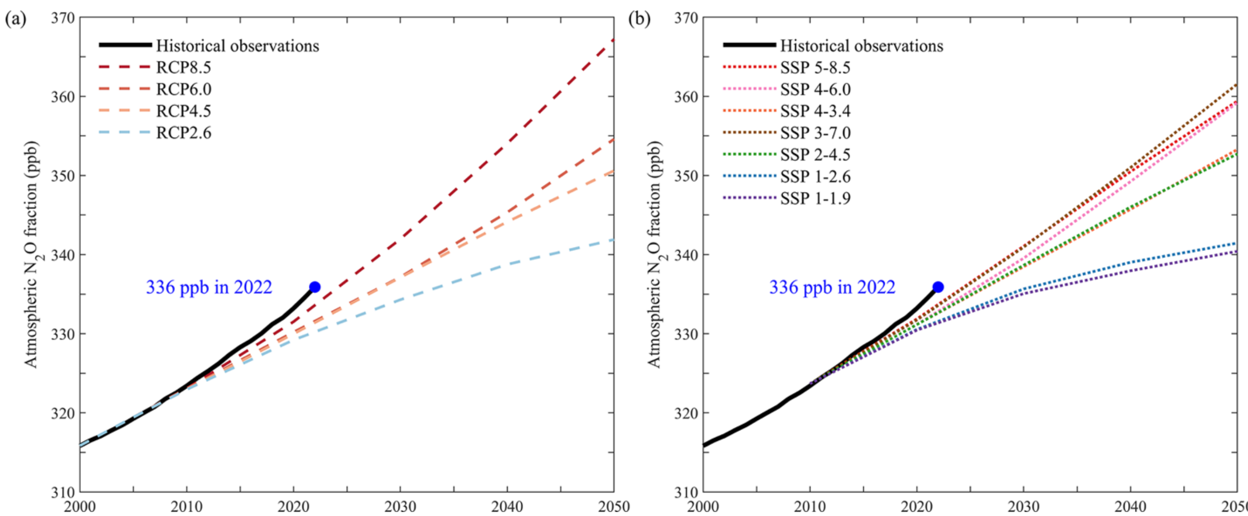

Figure 1. Historical N_2O emissions plotted against representative emissions scenarios and socioeconomic pathways used by the IPCC. Source: Tian, et al., "Global nitrous oxide budget (1980–2020)."

Restoration of the ozone layer. In addition to being a potent greenhouse gas, nitrous oxide also destroys the ozone layer. In fact, N_2O is the most important ozone-depleting substance (ODS) not currently controlled by the Montreal Protocol on Substances that Deplete the Ozone Layer, the overwhelmingly successful treaty agreed in 1987 to phase out production and consumption of chlorofluorocarbons and other ODSs and amended in 2016 to phasedown hydrofluorocarbons.[viii] If N_2O emissions continue to rise, the recovery of the ozone layer could be delayed significantly.[ix] Such a delay could adversely impact human health by increasing exposure to harmful ultraviolet (UV) rays that cause skin cancer and cataracts.[x] In fact, if the world were to act on carbon dioxide and methane but not N_2O, the incidence of certain skin cancers could increase by almost 10% by end of the century, depending on latitude.[xi] In addition, a delay could expose crops to UV levels beyond what they can tolerate and shift pollinator habits away from their plant hosts, potentially impacting food security.[xii] Finally, a delay could impact both terrestrial and aquatic biodiversity by, for example, shifting habitats and exacerbating stress on coral reef ecosystems.[xiii]

Human health and biodiversity. Some of the activities that drive nitrous oxide emissions, such as overapplication of fertilizer, are also responsible for other forms of nitrogen pollution. This is because of a unique property of the global nitrogen cycle scientists call "the nitrogen cascade."[xiv] Unlike the type of nitrogen that makes up 78% of the atmosphere (N_2), which is highly stable and cannot be used directly by plants, other types of nitrogen are far less stable and readily change from one to the other.[xv] These so-called "reactive" forms of nitrogen include ammonia (NH_3), nitric oxide (NO) and nitrogen dioxide (NO_2) (collectively known as nitrogen oxides or "NO_x"), and nitrate (NO_3^-), among other compounds. Nitrogen expert David Kanter helpfully explains these dynamics as follows: "an N atom may first be applied to a field as N fertilizer, before being first volatized as NH_3 or NO_x …; it may then be deposited, oxidized, and subsequently leached into a waterway as NO_3^-…; the same N atom could then be denitrified to N_2O…."[xvi]

These other nitrogen compounds are associated with adverse effects on human health, biodiversity, and ecosystems.[xvii] For instance, nitrogen dioxide (NO_2) can damage the lungs at high concentrations; at the lower concentrations more typical for ambient levels, NO_2 can cause coughing, headaches, loss of appetite, and stomach problems and has been shown to increase children's risk of developing respiratory diseases.[xviii] In addition, ammonia and NO_x can interact with other air pollutants to form microscopic particles (PM2.5) that cause respiratory diseases and cancer.[xix] In China alone, nitrogen pollution's air quality impacts have been estimated to cost the country as much as $62 billion per year.[xx] To cite just one more example: nitrate and ammonia from fertilizer use and manure can cause excessively high concentrations of nitrogen in marine and freshwater ecosystems, a phenomenon known as eutrophication.[xxi] These elevated levels of nitrogen lead, in turn, to overgrowth of algae and bacteria that release toxic compounds and deplete oxygen in the water, causing large-scale die-offs of fish and other aquatic organisms (so-called "dead zones"). A 2008 global review identified 415 coastal ecosystems affected by eutrophication.[xxii]

For this reason, efforts to mitigate N_2O emissions can help to address the negative impacts of other forms of nitrogen pollution as well.[xxiii] For instance, the Global Nitrous Oxide Assessment found that, in the context of an integrated approach to nitrogen management, an ambitious nitrous oxide mitigation effort could prevent over one million premature deaths per year due to air pollution by mid-century while reducing the incidence of asthma, respiratory hospitalizations, pre-term births, and ER visits.[xxiv] Nor would we need to wait until 2050 to see public health benefits of such an effort: in the next 10 years alone, ambitious mitigation efforts could help to avoid 4 million premature deaths.[xxv] Strikingly, the co-benefits of such a comprehensive effort to reduce N_2O emissions are so large that they overwhelmingly outweigh the costs; the benefits for the climate and ozone layer only strengthen the case for action.[xxvi]

2. Major N_2O Sources and Trends

Accounting for about three quarters of human-caused emissions, agriculture is the most significant driver of N_2O emissions by far.[xxvii] This figure combines direct emissions from fertilizer and manure, as well as indirect emissions from soils, streams, rivers, lakes, and oceans, where much of the nitrogen from fertilizer and manure ends up. The majority of agricultural N_2O emissions come from fertilizer, with nearly all of the remainder coming from manure.[xxviii] Other major sources of nitrous oxide emissions include fossil fuels, waste, industrial processes (particularly the production of adipic acid and nitric acid, feedstocks for the production of nylon and other synthetic materials), and biomass burning.[xxix] See Figure 2 below.

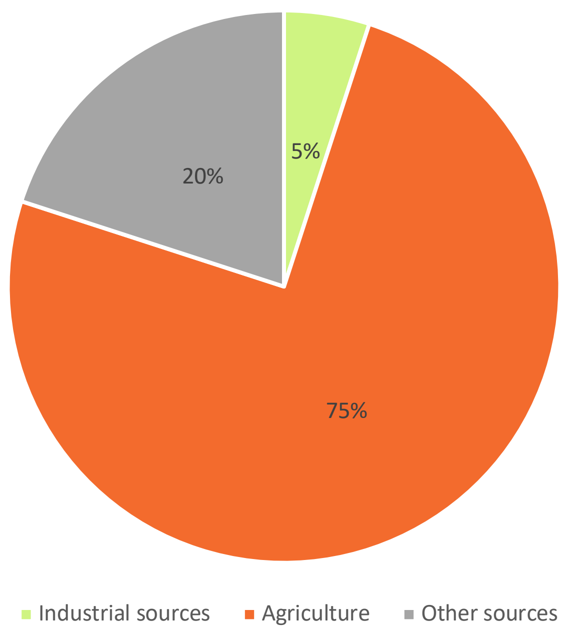

Figure 2. Major anthropogenic sources of nitrous oxide. Data from the Global Nitrous Oxide Assessment.

In addition to being the largest source of N_2O emissions, agriculture is also the primary driver of the increase in emissions over the last 4 decades.[xxx] This is due both to increased use of fertilizer and growth in animal agriculture, particularly cattle.[xxxi]

Countries' contributions to N_2O emissions vary widely, with a small number of countries responsible for the vast majority of emissions. In fact, two thirds of the world's N_2O

emissions come from G20 countries, and more than half come from just six countries and the EU.[xxxii] See Figure 3 below.

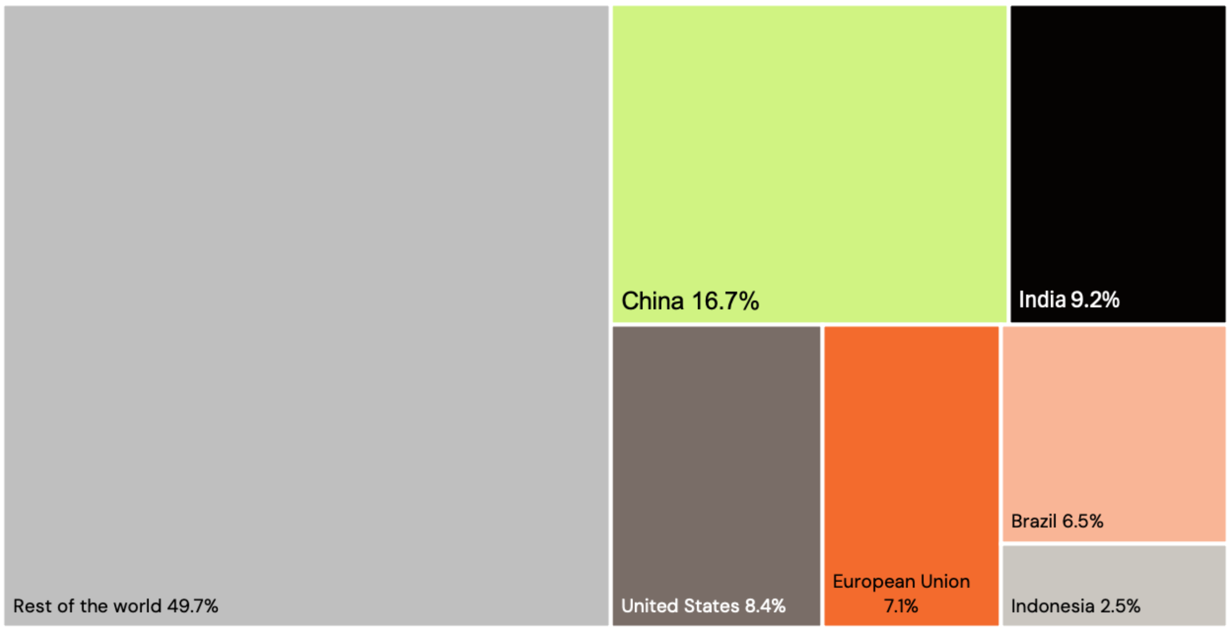

Figure 3. Top nitrous oxide emitters. Data from Climate Watch.

3. N_2O Mitigation Strategies & Challenges

N_2O emissions from energy and industrial sources are the easiest to abate by far. Emissions from fossil fuels will largely be dealt with in the transition from coal and oil to gas and renewables. For applications where continued burning of fossil fuels is necessary, it is possible to lower emissions by as much as 80% using existing technologies.[xxxiii] Similarly, for nitric and adipic acid production (the primary industrial sources of nitrous oxide), technology already exists to reduce emissions by up to 99%, though reductions of 90-95% are more common.[xxxiv] With nearly 80% of emissions coming from the United States and China alone, emissions from nitric and adipic acid production are also highly geographically concentrated, meaning that concerted action by just these two countries could eliminate the vast majority of industrial emissions.[xxxv]

Because the lion's share of N_2O emissions come from fertilizer, many of the most promising strategies for mitigating agricultural emissions involve reducing fertilizer use in one way or another. Because the downside risk of overapplication of fertilizer is considerably lower than that of underapplication, farmers often overapply fertilizer. Unfortunately, any nitrogen not absorbed by crops finds its way into the broader environment, a significant portion of it as nitrous oxide. Consequently, several methods for reducing fertilizer use focus on preventing overapplication by helping farmers to more accurately assess their fertilizer needs. In developed countries, farmers can do so using sophisticated sensors, computer software, and web-based tools.[xxxvi] In contexts where farmers do not have access to or cannot afford this technology, other options exist, such as leaf color charts that help them decide whether or not to apply more fertilizer based on the color of their crops' leaves.[xxxvii]

Though these sorts of tools can be effective at reducing emissions, several obstacles stand in the way of wider uptake.[xxxviii] One such obstacle is the lack of adequate support to facilitate their adoption. For instance, farmers may lack adequate internet access to use web-based tools, or they may need but lack access to extension services that disseminate and train them to use existing tools. In addition, some tools do not adequately account for contextual factors, such as availability and cost of fertilizer or local agroecological conditions. Finally, in addition to various forms of support for farmers and refinements to existing tools, social scientific research aimed at better understanding how and why farmers use fertilizer the ways they do could help to facilitate key practice changes.[xxxix]

Other strategies to reduce N_2O emissions from fertilizer use include developing novel crop varieties that require less fertilizer,[xl] slow- and controlled-release fertilizers that release nitrogen more slowly than conventional varieties,[xli] microbial fertilizers that pull nitrogen from the air and deliver it to plants' root systems,[xlii] and nitrification inhibitors that delay the conversion of ammonia in soil to nitrate. These technologies are at varying stages of commercial readiness, and there is a real need for additional funding for innovation in this space.[xliii] One important obstacle to the uptake of novel solutions like these is risk aversion among farmers, who tend to have small margins and so are reluctant to try new strategies that may adversely impact yields or profits.

In short, while solutions exist to reduce emissions from fertilizer use, many are imperfect, and there are non-trivial obstacles to wider uptake. Even so, there is significant potential to reduce emissions: according to one recent estimate, emissions from fertilizer use could be reduced by more than 50% by 2050 using currently available technologies.[xliv, 1]

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[1] One set of readers will wonder whether a significant reduction in fertilizer use is compatible with food security. The answer is yes: because there is considerable scope to improve efficiency, it is possible to substantially reduce fertilizer use without reducing yields. See Baojing Gu et al., "Cost-Effective Mitigation of Nitrogen Pollution from Global Croplands," *Nature* 613, no. 7942 (January 2023): 77–84, https://doi.org/10.1038/s41586-022-05481-8. Another set of readers will wonder about reducing synthetic fertilizer use much further, perhaps to zero. Doing so would of course be possible, but if we are to produce enough food to feed a future population of 9-10 billion, those reductions would need to be accompanied either by significant, population-scale dietary shifts away from animal products or a massive increase in the amount of land used for agriculture, an increase that would lead, in turn, to significant deforestation and biodiversity losses. See discussion at Einarsson, "Nitrogen in the Food System," sec. 7.1.

There are also a variety of strategies for reducing N_2O emissions from manure. These include optimizing the protein-to-energy ratio in ruminants' diets, either by using forages with a higher energy-to-protein ratio or by using high-energy feed supplements; using nitrification inhibitors on pasture; reducing grazing intensity; and using different manure management strategies, including using urease inhibitors, anaerobic digestion, and acidification.[xlv] As is true for many livestock sector mitigation strategies, a challenge for some of these solutions is that, while implementing them requires additional time, effort, and/or money on the part of farmers, farmers themselves see little or no benefit from doing so, at least in jurisdictions where no relevant policy incentives have been put in place. As a result, farmers in these jurisdictions have significant incentives not to do so. If these solutions are to come into wider use, steps will need to be taken to change farmers' incentives.[xlvi]

Finally, it bears noting that the composition of human diets has a significant impact on nitrous oxide emissions. Generally speaking, animal-based foods are responsible for significantly greater nitrogen pollution than are plant foods.[xlvii] This is partly because of the large contribution manure makes to nitrogen pollution, but it also has to do with the fact that animals are highly inefficient at converting feed to food: only about 2% of the calories fed to a cow as feed or forage are converted to beef; for pigs and chickens, the corresponding figures are 8.6% and 13%, respectively.[xlviii] More specifically, and more relevantly for present purposes, much of the nitrogen animals take in through food ends up secreted as waste rather than in the meat, milk, and eggs they produce.[xlix] Consequently, far more grains and other feed crops must be produced to support dietary patterns high in animal products than for more plant-based diets.[l] In fact, only around half the world's cereals and about a fifth of its soy are used for human food, with about a third of cereals and nearly three quarters of soy used to feed animals.[li] As a result, diets richer in plant-based foods are associated with lower levels of nitrogen pollution than those with a higher proportion of animal products, not just for the obvious reason that the former are associated with lower levels of manure, but also because the amount of crops that must be grown to support such diets—and so the amount of fertilizer used—is substantially lower.[lii] A 2013 UNEP report found that combining dietary changes and reductions in food loss and waste with measures to improve the efficiency of crop and livestock production and improve manure recycling results in about 50% greater emissions reductions than technical measures alone.[liii] More recent modeling done as part of the Global Nitrous Oxide Assessment arrived at a similar result.[liv]

Notwithstanding the various challenges and obstacles to mitigation described in this section, the Global Nitrous Oxide Assessment found that a highly ambitious effort to reduce N2O emissions could reduce emissions by more than 40% compared to 2020 levels by 2050.[lv]

4. Important Recent Developments

This section summarizes recent developments at the international level related to nitrous oxide, including actions by governments, notable recent and forthcoming publications, and announcements by philanthropies.

On nitrogen generally, there have been at least two important developments in the last five years. First, some efforts have been made to establish a mechanism for coordinating nitrogen policies between governments and across international conventions. The process began in March 2019, when the United Nations Environment Assembly (UNEA) adopted the Sustainable Nitrogen Management Resolution, which recognizes the environmental and climate harms of nitrogen pollution, emphasizes the need to coordinate disparate global nitrogen initiatives, and calls on the UNEP's executive director to "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."[lvi] In a subsequent meeting of the International Nitrogen Management System (INMS), the decision was made to proceed with establishing an inter-convention nitrogen coordination mechanism (INCOM).[lvii] INMS is now following up with member states through the UNEP Nitrogen Working Group to prepare the basis for establishing INCOM. Second, international consensus has emerged around the need to halve nutrient pollution by 2030. In 2019, 30 UN member states adopted the *Colombo Declaration on Sustainable Nitrogen Management*, parties to which agree to develop national nitrogen action plans that include a goal of halving nitrogen waste by 2030 and to adopt the *Roadmap for Action on Sustainable Nitrogen Management 2020–2022*.[lviii] Similar targets subsequently made their way into the EU's 2020 Farm to Fork strategy, which includes a goal of reducing nutrient losses by 50%, and the Kunming-Montreal Biodiversity Framework, adopted in 2022, which includes a goal of "reducing excess nutrients lost to the environment by at least half" by 2030.[lix]

In the last two years, there have also been some notable developments focused on climate super pollutants, a class of exceptionally powerful greenhouse gases that includes nitrous oxide.[lx] First, a group of 11 philanthropies announced at COP28 that they would be investing $450 million over the next three years to catalyze faster phase-down of non-CO_2 super pollutants.[lxi] Then, on July 23 of this year, the White House held a Super Pollutants Summit in which N_2O emissions featured prominently. Subsequently, at the September 2024 meeting of the U.S.-China Working Group on Enhancing Climate Action in the 2020s, the United States and China reaffirmed that the two countries will co-host a "Methane and Other Non-CO2 Greenhouse Gases Summit" in Baku, Azerbaijan during COP29.[lxii]

Finally, there have been a few notable developments on N_2O specifically. Early this summer, Hanquin Tian and colleagues published an updated "global N_2O budget" that includes estimates of the contribution of the main N_2O sources and sinks, regional emissions figures, and historical data showing trends over time.[lxiii] In early November 2024, the UNEP-convened Climate and Clean Air Coalition published a global N_2O assessment that includes discussion of key mitigation strategies and mitigation potential estimates. This N_2O assessment will eventually be accompanied by the more comprehensive International Nitrogen Assessment, which is expected to be published in 2025. All of this comes on the heels of the Sunnylands Statement, issued following talks between U.S. Special Presidential Envoy for Climate John Kerry and China Special Envoy for Climate Change Xie Zhenhua in early November of 2023, which includes a commitment "to cooperate on respective measures to manage nitrous oxide emissions."[lxiv]

As these recent developments make clear, momentum is building for international cooperation on N_2O.

5. How to Advance N_2O Mitigation at the International Level

What, then, should world leaders do to advance N_2O mitigation? This section offers recommendations for the international community.

Countries should start by including N_2O targets, sectoral mitigation strategies, and action plans in their voluntary commitments under the Paris Climate Agreement, known as Nationally Determined Contributions or NDCs, as recommended in guidance recently released by the UNEP-convened Climate & Clean Air Coalition.[lxv] The next round of NDCs is due early next year.

In addition, **the international community should give serious consideration to the creation of a global framework for the reduction of N_2O emissions.** The Montreal Protocol is perhaps the most obvious forum for such a regime, given that (1) N_2O is the most potent ozone-depleting substance not regulated under the Protocol, (2) the Montreal Protocol has been successful in controlling other ozone-depleting and greenhouse-gas substances, and (3) the Protocol has already been used to address another ozone-depleting substance widely used in agriculture, methyl bromide. While Montreal Protocol parties and experts are considering their responses to the findings of the UNEP and FAO

Global N_2O Assessment, other forums should be considered, as well. Regardless of the forum for action on N_2O, the international community should take care to craft a global N_2O reduction framework that advances global sustainable development goals broadly.

The creation of a global N_2O reduction framework is a complex, weighty matter, and it will likely take some time for the international community to achieve consensus regarding the utility and character of any such regime. As important as it is to take the time necessary to work through the relevant considerations carefully, the complexity of the issues and the difficulty of negotiations need not and should not stand in the way of earlier action now. The enormously successful recent efforts to catalyze international action on methane offer a promising roadmap for countries to advance N_2O mitigation efforts while discussions proceed.

Just a few months after the publication of a landmark scientific assessment of methane emissions called the Global Methane Assessment, the United States and the European Union announced the Global Methane Pledge, a voluntary effort to reduce methane emissions 30% by 2030. Just a few months later, in May 2022, a re-grantor called the Global Methane Hub was launched to offer grants and technical support to implement the Methane Pledge. As of March 2024, the Methane Pledge has 158 participants.[lxvi] The Methane Hub has been similarly successful, distributing $84 million toward methane projects in 2023 and catalyzing hundreds of millions of dollars of additional investment in the short time since it was founded.[lxvii] Global political pledges and international financial support have spurred the development of national methane reduction policies in many jurisdictions, including Canada, China, the European Union, Germany, Nigeria, South Korea, and the United States, among others.[lxviii] The combination of global political attention, national level regulatory action, and financial assistance has accelerated progress in addressing methane emissions, which is now front and center in international climate cooperation.

World leaders should take a similar approach to nitrous oxide.

First, to focus the world's attention on the issue and create consensus around the appropriate level of ambition on N_2O, **the United States should work with other countries to assemble a coalition of the willing to commit to a time-bound, quantitative N_2O mitigation goal akin to the Global Methane Pledge**. As for what that goal should be, it was noted above in Section 1 that emissions must fall around 22% by 2050 to limit warming to 1.5 degrees Celsius. In addition to being in line with the temperature goals agreed to at the 21st conference of the parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC), the foundational treaty underlying the Paris Climate Agreement, we know it is possible to reduce emissions to that level: the Global Nitrous Oxide Assessment found that a 22% reduction is achievable using technical measures alone, while reductions of more than 40% by 2050 are feasible if not also immensely difficult to achieve.[lxix] Regardless of the exact target, any pledge agreed to by countries should include language stressing the need to take an integrated approach to nitrogen management to avoid the kind of pollution swapping that can result from focusing narrowly on any single nitrogen compound.

In addition to a 2050 goal for overall N_2O emissions, **countries should set a near-term goal of eliminating emissions from industrial sources**, since these emissions are far easier to abate than emissions from other sources. Because the technology already exists and is ready to deploy, 2030 or, at the latest, 2035 would seem to be a reasonable target year for eliminating industrial emissions.

To facilitate the achievement of these mitigation goals, **world leaders should make a collective commitment to marshal the necessary funding**. This commitment could be modeled on Mission Innovation, the public-private collaboration to increase public and private funding for clean energy innovation announced in 2015. In addition to funding mitigation-related activities directly, countries could rally philanthropies to establish a re-grantor modeled on the Global Methane Hub. Alternatively, a group of philanthropies could pledge to coordinate their grantmaking with a view to advancing efforts to achieve global N_2O mitigation goals. Regardless, funding could go to a variety of project types, from research into innovative agricultural mitigation solutions to social scientific research aimed at understanding issues such as how and why farmers use fertilizers the way they do and what factors could help to facilitate key practice changes.[lxx]

These three steps by the international community could catalyze a global effort to address the third most important greenhouse gas, just as the Methane Pledge and Methane Hub have for methane. In addition to helping to lay the foundation for the development of a global framework for reducing N_2O emissions, this would be a major win for air and water quality, biodiversity, and human health.[lxxi]

Learn more about the N_2O Hub and share your interest in joining at n2oaction.org and follow us on LinkedIn.

[i] Forster, P., *et. al.*, Ch. 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity, in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Masson-Delmotte, V., et al., (Cambridge, United Kingdom and New York, NY: Cambridge University Press, 2021), pp. 923–1054, DOI: 10.1017/9781009157896.009. See Table 7.15.

[ii] Hanquin Tian, et al., "Global nitrous oxide budget (1980–2020)," *Earth Syst. Sci. Data* 16 (2024): 2543–2604, https://doi.org/10.5194/essd-16-2543-2024, Fig. 5.

[iii] United Nations Environment Programme and Food and Agriculture Organization, *Global Nitrous Oxide Assessment*, Nairobi, Kenya, 2024, https://doi.org/10.59117/20.500.11822/46562, sec. 4.1.2. Cited hereafter as "Global Nitrous Oxide Assessment."

[iv] Global Nitrous Oxide Assessment, sec. 4.2.4.

[v] Global Nitrous Oxide assessment, sec. 2.1.

[vi] See Table SPM.2 in IPCC, *2013: Summary for Policymakers*, in *Climate Change 2013: The Physical Science Basis*, contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed. T.F. Stocker, et al., (Cambridge and New York: Cambridge University Press, Cambridge, 2013) and Table SPM.1 in IPCC, *2021: Summary for Policymakers*, in *Climate Change 2021: The Physical Science Basis,* contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, ed. V. Masson-Delmotte, et al., (Cambridge and New York: Cambridge University Press, 2021), pp. 3-32, doi:10.1017/9781009157896.001.

[vii] See Rogelj, J., and Lamboll, R.D., "Substantial reductions in non-CO2 greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget," *Commun Earth Environ* 5 (2024): 35, https://doi.org/10.1038/s43247-023-01168-8, Table 1.

[viii] See "Montreal Protocol on Substances that Deplete the Ozone Layer," adopted September 16, 1987, United Nations Treaty Collection, https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2-a&chapter=27&clang=_en;"Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer," adopted October 15, 2016, United Nations Treaty Collection, https://treaties.un.org/doc/Publication/MTDSG/Volume%20II/Chapter%20XXVII/XXVII-2-f.en.pdf; and Ravishankara, A. R. et al. Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st

Century," Science 326 (2009): 123–125. https://doi.org/10.1126/science.1176985.

[ix] Global Nitrous Oxide Assessment, sec. 4.2.4. Cf. AH Butler, et al., "Diverse policy implications for future ozone and surface UV in a changing climate," *Environmental Research Letters* 11, no. 6 (2016), DOI: 10.1088/1748-9326/11/6/064017.

[x] Global Nitrous Oxide Assessment, sec. 4.2.5.

[xi] Ibid.

[xii] UNEP Ozone Secretariat, *Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change: 2022 Assessment Report*, March 2023, https://ozone.unep.org/system/files/documents/EEAP-2022-Assessment-Report-May2023.pdf, ch. 4.

[xiii] Ibid., chs. 4-5.

[xiv] James N. Galloway, et al., "The Nitrogen Cascade," *BioScience* 53, no. 4 (April 1, 2003): 341–56, https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2.

[xv] Galloway et al.

[xvi] David R. Kanter, "Nitrogen pollution: a key building block for addressing climate change," *Climatic Change* 147 (2018): 11–21, https://doi.org/10.1007/s10584-017-2126-6.

[xvii] For a summary of these effects with references to additional sources, see Rasmus Einarsson, "Nitrogen in the food system," TABLE Explainer, TABLE, University of Oxford, Swedish University of Agricultural Sciences, and Wageningen University and Research, February 2024, https://doi.org/10.56661/2fa45626, Table 1.

[xviii] J.W. Erisman, et al., "Consequences of human modification of the global nitrogen cycle," *Phil Trans R Soc B* 368 (2013): 20130116, http://dx.doi.org/10.1098/rstb.2013.0116, p. 2.

[xix] In addition to the sources cited in Einarsson, "Nitrogen in the food system," see Lelieveld, J., Evans, J., Fnais, M. et al., "The contribution of outdoor air pollution sources to premature mortality on a global scale," *Nature* 525 (2015): 367–371, https://doi.org/10.1038/nature15371.

[xx] Beojing Gu, et al., "Atmospheric Reactive Nitrogen in China: Sources, Recent Trends, and Damage Costs," *Environmental Science & Technology* 46, no. 17 (2012): 9420–9427, https://pubs.acs.org/doi/10.1021/es301446g.

[xxi] Erisman, et al., "Consequences of human modification of the global nitrogen cycle," p. 4.

[xxii] Mindy Selman, Zachary Sugg, and Suzie Greenhalgh, *Eutrophication and Hypoxia in Coastal Areas*, World Resrouces Institute, 2008, https://www.wri.org/research/eutrophication-and-hypoxia-coastal-areas.

[xxiii] For a real-world example of this phenomenon, see Guo, Y., Chen, Y., Searchinger, T.D. et al., "Air quality, nitrogen use efficiency and food security in China are improved by cost-effective agricultural nitrogen management," *Nat Food* 1 (2020): 648–658, https://doi.org/10.1038/s43016-020-00162-z.

[xxiv] Global Nitrous Oxide Assessment, sec. 4.1.3.

[xxv] Ibid.

[xxvi] See Kanter, et al., "Nitrogen Pollution," sec. 4 and David R. Kanter, et al., "Managing a Forgotten Greenhouse Gas under Existing U.S. Law: An Interdisciplinary Analysis," *Environmental Science & Policy* 67 (January 1, 2017): 44–51, https://doi.org/10.1016/j.envsci.2016.11.003.

[xxvii] In addition to the Climate Watch data represented in Figure 2, see Tian, et al., "Global nitrous oxide budget (1980–2020)."

[xxviii] Tian, et al., "Global nitrous oxide budget (1980–2020)." See Table 3.

[xxix] Ibid.

[xxx] Ibid., esp. pp. 2574-2575.

[xxxi] Ibid., p. 2558 and Table 3.

[xxxii] Using data from Climate Watch (Washington, D.C.: World Resources Institute, 2024), available online at https://www.climatewatchdata.org/. Accessed July 8, 2024.

[xxxiii] Eric A. Davidson and Wilfried Winiwarter, "Urgent abatement of industrial sources of nitrous oxide," *Nature Climate Change* 13 (2023): 599-601, https://doi.org/10.1038/s41558-023-01723-3.

[xxxiv] Ibid. Cf. Ali Hasanbeigi and Adam Sibal, "Stopping a Super-Pollutant: N_2O Emissions Abatement from Global Adipic Acid Production," Global Efficiency Intelligence, April 2023, https://www.globalefficiencyintel.com/stopping-a-superpollutant-n2o-emissions-abatement-from-global-adipic-acid-production.

[xxxv] Davidson and Winiwarter, "Urgent abatement of industrial sources of nitrous oxide," Table 2.

[xxxvi] Gabrielle Dreyfus, Caitlan Frederick, Emily Larkin, Yifan Powers, and Jagori Chatterjee, "Reducing Nitrous Oxide Emissions From Smallholder Farmer Agriculture Through Site Specific Nutrient Management," Precision Development and the Institute for Governance and Sustainable Development, 2023, https://www.igsd.org/publications/reducing-nitrous-oxide-emissions-from-smallholder-farmer-agriculture-through-site-specific-nutrient-management/.

[xxxvii] Dreyfus, et al., "Reducing Nitrous Oxide Emissions From Smallholder Farmer Agriculture Through Site Specific Nutrient Management."

[xxxviii] This paragraph draws on the excellent summary of obstacles to wider use of site-specific nutrient management strategies in Dreyfus, et al., "Reducing Nitrous Oxide Emissions From Smallholder Farmer Agriculture Through Site Specific Nutrient Management," sec. 5.

[xxxix] The need for social-scientific research to inform nitrous oxide policy is emphasized by the Global Nitrous Oxide Assessment (see. Sec. 6.3.4) as well as by Dreyfus, et al., "Reducing Nitrous Oxide Emissions From Smallholder Farmer Agriculture Through Site Specific Nutrient Management," p. 14 and David R. Kanter, Stephen Del Grosso, Clemens Scheer, David E. Pelster, and James N. Galloway, "Why future nitrogen research needs the social sciences," *Current Opinion in Environmental Sustainability* 47 (December 2020): 54-60, https://doi.org/10.1016/j.cosust.2020.07.002.

[xl] See, for instance, https://www.maizegenetics.net/cerca.

[xli] Dora Lawrencia et al., "Controlled Release Fertilizers: A Review on Coating Materials and Mechanism of Release," *Plants* 10, no. 2 (February 2021): 238, https://doi.org/10.3390/plants10020238.

[xlii] Aidan Connolly, "Are Microbes The Future Of Fertilizer?," *Forbes*, April 24, 2023, https://www.forbes.com/councils/forbestechcouncil/2023/04/24/are-microbes-the-future-of-fertilizer/.

[xliii] David R. Kanter, Stephen M. Ogle, and Wilfred Winiwarter emphasize the need for governments to drive innovation in agricultural nitrous oxide solutions on p. 9 of their "Building on Paris: integrating nitrous oxide mitigation into future climate policy," *Current Opinion in Environmental Sustainability* 47 (December 2020): 7-12, https://doi.org/10.1016/j.cosust.2020.04.005.

[xliv] See Y. Gao and A. Cabrera Serrenho, "Greenhouse gas emissions from nitrogen fertilisers could be reduced by up to one-fifth of current levels by 2050 with combined interventions," *Nat Food* 4 (2023): 170–178, https://doi.org/10.1038/s43016-023-00698-w. The authors find that measures to reduce demand for fertilizer could reduce emissions by 51.6% and that, when these measures are combined with nitrification inhibitors and a variety of measures to reduce emissions from fertilizer production, total fertilizer emissions could be reduced by 78%. They do not give a figure for demand reduction measures and nitrification inhibitors deployed in concert, but presumably it would be somewhere between 51 and 78%.

[xlv] The latter two manure management strategies are discussed in Yan, Xiaojie et al. "A review of mitigation technologies and management strategies for greenhouse gas and air pollutant emissions in livestock production," *Journal of environmental management* 352 (2024): 120028, doi:10.1016/j.jenvman.2024.120028.

[xlvi] While this is generally true, there are some exceptions. For instance, significant incentives exist in California for digesters through the Low Carbon Fuel Standard; see California Air Resources Board, Session 9: Overview of Low Carbon Fuel Standard & Dairy/Swine Manure Fuel Pathways, March 29, 2022, https://ww2.arb.ca.gov/sites/default/ f iles/2022-04/dairy-ws-session-9-CARB.pdf.

[xlvii] See J. Poore and T. Nemecek, "Reducing food's environmental impacts through producers and consumers," *Science* 360 (2018): 987-992, DOI:10.1126/science.aaq0216, Figure 1; H. Westhoek, et al., *Nitrogen on the Table: The influence*

of food choices on nitrogen emissions and the European environment, European Nitrogen Assessment

Special Report on Nitrogen and Food, (Edinburgh, UK: Centre for Ecology & Hydrology, 2015), available at https://nora.nerc.ac.uk/id/eprint/513111/; and Gidon Eshel, Alon Shepon, Tamar Makov, and Ron Milo, "Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States," *PNAS* 111, no. 33 (July 2014): 11996-12001, https://doi.org/10.1073/pnas.1402183111.

[xlviii] Hannah Ritchie, "If the world adopted a plant-based diet we would reduce global agricultural land use from 4 to 1 billion hectares," *Our World in Data*, March 4, 2021, https://ourworldindata.org/land-use-diets.

[xlix] See Westhoek, et al., *Nitrogen on the Table*, Figure 2.7.

[l] Ritchie, "If the world adopted a plant-based diet we would reduce global agricultural land use from 4 to 1 billion hectares."

[li] Ibid. and Hannah Ritchie and Max Roser, "Forests and Deforestation," *Our World in Data*, 2021, https://ourworldindata.org/forests-and-deforestation.

[lii] Global Nitrous Oxide Assessment, secs. 5.3 and 5.4.

[liii] UNEP, *Drawing Down N_2O to Protect Climate and the Ozone Layer: A UNEP Synthesis Report*, United Nations Environment Programme (UNEP), (Nairobi, Kenya: 2013), https://www.unep.org/resources/report/drawing-down-n2o-protect-climate-and-ozone-layer-unep-synthesis-report, Table 4.4. Other estimates suggest that dietary changes could reduce food system nitrogen losses by 10-40%. Einarsson, "Nitrogen in the Food System," p. 32 and sec. 6.3.

[liv] Global Nitrous Oxide Assessment, Table 3.2.

[lv] Ibid.

[lvi] UNEP/EA.4/Res.14 (2019). Resolution Adopted by the United Nations Environment Assembly on 15 March 2019, Sustainable Nitrogen Management, Nairobi, Kenya. Available at https://wedocs.unep.org/bitstream/handle/20.500.11822/28478/English.pdf.

[lvii] Mark A. Sutton, et al., "The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond," *One Earth* 4 (2021): 10-14, https://doi.org/10.1016/j.oneear.2020.12.016.

[lviii] *Colombo Declaration on Sustainable Nitrogen Management*, available at https://www.inms.international/sites/inms.international/files/Colombo%20Declaration_Final.pdf.

[lix] See European Commission, *A Farm to Fork Strategy for a fair, healthy and environmentally friendly food system*, 2020, https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf and Kunming-Montreal Global Biodiversity Framework, Decision 15/4 of the Conference of the Parties to the Convention on Biological Diversity, 2022, https://www.cbd.int/gbf.

[lx] See, e.g., https://www.ccacoalition.org/news/climate-super-pollutants.

[lxi] "Climate Philanthropies Announce $450 Million to Deepen Investment in Super Climate Pollutants," *PR Newswire*, December 2, 2023, https://www.prnewswire.com/news-releases/climate-philanthropies-announce-450-million-to-deepen-investment-in-super-climate-pollutants-302003534.html.

[lxii] U.S. Department of State, "Second Meeting of U.S.-China Working Group on Enhancing Climate Action in the 2020s," September 8, 2024, https://www.state.gov/second-meeting-of-u-s-china-working-group-on-enhancing-climate-action-in-the-2020s/.

[lxiii] Tian, et al., "Global nitrous oxide budget (1980–2020)."

[lxiv] "Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis," U.S. Department of State, November 14, 2023, https://www.state.gov/sunnylands-statement-on-enhancing-cooperation-to-address-the-climate-crisis/.

[lxv] Climate and Clean Air Coalition, "Leveraging the Benefits of non-CO_2 Pollutants and Air Quality in NDC 3.0: Guidance on Including N_2O in Nationally Determined Contributions," 2024, available at https://www.ccacoalition.org/resources/key-messages-nitrous-oxide-n2o-guidance-ndcs.

[lxvi] See "Pledges," Global Methane Pledge, available at https://www.globalmethanepledge.org/#pledges (accessed October 16, 2024).

[lxvii] Global Methane Hub, Annual Impact Report, 2023, https://www.globalmethanehub.org/wp-content/uploads/2024/04/GMH_AnnualImpactReport_2023_Digital.pdf.

[lxviii] Details on all these plans are available through the IEA's policy database: https://www.iea.org/policies?topic%5B0%5D=Methane%20abatement.

[lxix] Global Nitrous Oxide Assessment, Table 3.2.

[lxx] David R. Kanter, Stephen M. Ogle, and Wilfred Winiwarter emphasize the need for governments to drive innovation in agricultural nitrous oxide solutions on p. 9 of their "Building on Paris: integrating nitrous oxide mitigation into future climate policy," *Current Opinion in Environmental Sustainability* 47 (December 2020): 7-12, https://doi.org/10.1016/j.cosust.2020.04.005.

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