Global Carbon Project
GCP Office at Boston College
Center for Earth System Science and Global Sustainability (CES^3)

Briefing on key messages Global Nitrous Oxide Budget 2024

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This document is intended as a background briefing for the co-authors and journalists covering the release of the Global Nitrous Oxide Budget 1980-2020.
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The Global Carbon Project is an international research project within the Future Earth research initiative on global sustainability and a research partner of the World Climate Research Programme. It aims to develop a complete picture of the global carbon cycle and budgets of carbon dioxide, methane, and nitrous oxide, including both its biophysical and human dimensions, together with the interactions and feedbacks between them.

This Global Nitrous Oxide Budget 2024 is the second such budget and the first one as a living data collection in the journal *Earth System Science Data*. Data and methods are provided in the publication, with links at the end of this document.

Headline 1:
Global emissions of nitrous oxide (N_2O), a powerful greenhouse gas, continue to rise unabated, largely driven by unsustainable practices in global food production and growing food demand

Headline 2:
Atmospheric concentrations of N_2O, the third most important greenhouse gas, are increasing faster than predicted by the IPCC emission scenarios

Headline 3:
While global CO_2 emissions from human activities (fossil fuel and land use change) have been rather stable over the past decade, global N_2O emissions, largely from the production of food, continue to rise

We report the N_2O trends and budgets for the last four decades using observations, biospheric modeling, observation-upscaled synthesis products, activity-based inventories, and atmospheric observations and modeling. We report on a total of 18 natural and anthropogenic source sectors and 3 sinks of global N_2O. In what follows, we emphasize emissions from human activities relevant to climate change, the goals of the Paris Climate Agreement, and the national mitigation commitments.

Highlights

- N_2O emissions from human activities have increased by 40% (3 million metric tons of N_2O per year) in the past four decades.
- Agricultural production (due to the use of nitrogen fertilizers and animal manure) contributed 74% of the total anthropogenic N_2O emissions in the last decade.
- N_2O accumulation in the atmosphere has accelerated in the last four decades, with growth rates over the past three years (2020-2022) higher than any previous observed year since 1980 when reliable measurements began, and about 30% higher than in the past decade.
- The concentration of atmospheric N_2O reached 336 parts per billion in 2022 (the latest global data available), 25% above pre-industrial levels.
- The observed atmospheric N_2O concentrations in the past decade have exceeded the most pessimistic illustrative future GHG trajectories used by the IPCC that lead to global mean temperatures well above 3°C by the end of this century.
- For net-zero emission pathways consistent with the Paris Agreement (stabilizing global temperatures below 2°C from pre-industrial levels), anthropogenic N_2O emissions must decline by at least 20% relative to 2019 levels by 2050.
- The top five country emitters by volume of anthropogenic N_2O emissions in 2020 were China (16.7%), India (10.9%), USA (5.7%), Brazil (5.3%), and Russia (4.6%).
- The global ocean continues to be a source of N_2O and remains stable at about 7.4 million metric tons per year, with a large contribution from the global coastal oceans.
- The EU, Japan and Korea have successfully reduced anthropogenic N_2O emissions over the past decades. However, even with measurable increases in nitrogen use efficiency in agriculture in some regions, emissions from direct fertilizer and manure application have slightly increased or remained stable. China's anthropogenic N_2O emissions have been declining for the past five years owing to increased nitrogen use efficiency.
- Southern Africa and the Middle East have emissions from non-agricultural sources (industry, fossil fuel combustion and waste, biomass burning), which are comparable to, or higher, than the agricultural emissions, requiring different mitigation strategies.

Nitrous Oxide 101

1. Nitrous oxide (N_2O) is the third most important greenhouse gas (after carbon dioxide (CO_2) and methane (CH_4)), leading to human-induced global warming.
2. N_2O is 273 times more powerful greenhouse gas than CO_2 over a time horizon of 100 years.
3. N_2O emissions from human activities are responsible for 6.4% of the effective radiative forcing of greenhouse gases and have added about 0.1°C to current global warming.

The whole food supply chain involved in food production is responsible for ⅓ of all GHG emissions from human activities based on Xu et al 2021, Nature.

4. As a result of increased anthropogenic N_2O emissions, the N_2O concentration in the atmosphere is now 25% higher than its pre-industrial (1750) level.
5. In addition to climate impacts, N_2O is a stratospheric ozone-depleting substance, and its rise further delays the recovery of the stratospheric ozone hole.
6. Once emitted, N_2O stays in the atmosphere for longer than the average human life (117 years), and therefore its climate and ozone impacts are long-lived.
7. In addition to N_2O emissions, the inefficient use of synthetic nitrogen fertilizers and animal manure, also leads to the pollution of groundwater, drinking water, and inland and coastal waters.

Emissions and Atmospheric Accumulation

- Total annual N_2O emissions from human activities increased by 40% (or 3 Million metric tons per year) in the past four decades (1980-2020) and have continued to increase to 2022 (the latest global data available).
- These emissions have accumulated in the atmosphere at an increasing rate. The annual atmospheric N_2O growth increased from 5.2 million metric tons per year during the 2000s to almost 7.2 million metric tons per year in the 2010s. The growth has further accelerated over the past three years (2020-2022), with growth rates higher than any previously observed year since 1980 (the start year of this assessment), and about 30% higher than in the past decade.
- Atmospheric concentrations of N_2O reached 336 parts per billion in 2022, 25% above pre-industrial levels. The atmospheric increase is smaller than the emissions increase because chemical sinks remove some N_2O from the atmosphere.
- The observed atmospheric N_2O concentrations in recent years have exceeded the worst illustrative emissions scenarios used by the Intergovernmental Panel on Climate Change, underscoring the urgency to reduce anthropogenic N_2O emissions.

Sources of Anthropogenic Emissions

- The use of nitrogen fertilizers in agriculture, including livestock manure production and use, is the single largest anthropogenic emission source of N_2O to the atmosphere, and more than three times the emissions from the second biggest anthropogenic source.
- Growing demand for meat and dairy products has also contributed to an increase in emissions through the increase in manure production, which causes N2O emissions. Increased nitrogen fertilizers used in the production of animal feed have also contributed to the increase.
- Agricultural production contributed over 70% of the total anthropogenic N_2O emission in the last decade.
- Emissions from agriculture continue to grow, while other sectors, such as fossil fuels and the chemical industry, are globally not growing or declining.

- Aquaculture, with emissions of about one-tenth of those from the use of chemical fertilizers on land, is growing rapidly, particularly in China.
- As part of increased nitrogen loads on land (fertilization and manure), N_2O emissions from inland waters (e.g., reservoirs, lakes, ponds), estuaries, and coastal ecosystems have also increased.
- Human-induced climate change increases atmospheric CO_2, and deforestation indirectly affects soil N_2O fluxes in complex ways, increasing or decreasing.
- Fossil fuel combustion and certain industrial processes (production of nitric acid or adipic acid for the making of nylon) contribute 17% to anthropogenic emissions, partly at very high concentrations at the stack and hence offering great potential for abatement.

Top Regional and Country Anthropogenic Emitters

- The top five emitters by volume of anthropogenic N_2O emissions in 2020 were China (16.7%), India (10.9%), USA (5.7%), Brazil (5.3%), and Russia (4.6%). The per capita emissions (Kg N_2O/person) for the top five emitters are 1.3 (China), 0.8 (India), 1.7 (USA), 2.5 (Brazil), and 3.3 (Russia). Per capita emissions are influenced by both domestic consumption and trade of food/products.
- Anthropogenic N_2O emissions from four emerging economies (China, India, Brazil, and Turkey) have more than doubled their emissions, 135% (China), 157% (India), 131% (Brazil) and 117% (Turkey) relative to 1980. Direct nitrogen additions in agriculture are the main cause of the increase. However, China's anthropogenic N_2O emissions have been declining since 2016 because China has reduced the use of nitrogen fertilizer by about 5 million metric tons, from its peak of 31 million metric tons of nitrogen in 2015 to 26 million metric tons in 2020.
- Developing countries in Africa and South and Southeast Asia show a significant increase in N fertilizer use, albeit coming from low values. Among them, Pakistan and Ethiopia have grown N_2O emissions by over 200%.
- The EU, Japan and Korea have successfully reduced N_2O emissions over the past four decades. The EU reduced emissions by 31%, the largest decrease of any region, mostly due to reductions from fossil fuel and industry emissions in the 1990s; however, agricultural emissions have not declined over the past two decades.
- Total N_2O emissions from Korea and Japan reached a peak in the late 1990s and have decreased by about 30% since then. Emissions from fossil fuel and industry dominated the temporal variations of N_2O emissions from Korea and Japan, which increased from 0.06 million metric tons of N_2O in 1980 to 0.13 million metric tons of N_2O in 2000, and then decreased to 0.06 million metric tons of N_2O in 2020. Emissions from agriculture remained relatively stable in the past two decades.
- While Russia's total emissions declined during the 1990s due to the collapse of the Soviet Union, and have not fully returned to previous levels, emissions from using fertilizers and manure have increased since.
- USA: Agricultural N_2O emissions show an increase, but other direct emissions (including the sectors of 'Fossil fuel and industry, Waste and wastewater, and Biomass burning)

show a decrease so total anthropogenic N_2O emissions from the US were largely stable over the past two decades.
- Canada's N_2O emissions have increased over the past four decades due to nitrogen additions in agriculture.
- Brazil's emissions grew strongly over the past two decades, with direct emissions from the use of fertilizers and manure more than double.
- Northern African countries more than tripled their emissions growth rate, while equatorial countries doubled their emissions in the last two decades, but from low absolute levels.
- Southeast Asia, dominated by Indonesia, tripled its anthropogenic emissions during the last two decades.
- Australasian emissions (Australia and New Zealand) show little or no growth over the last two decades.

Implications for Reaching Net-Zero Emissions

- Current trends show that N_2O concentrations are increasing faster than the most pessimistic illustrative pathways of future trajectories used by the IPCC, contributing, along with other GHGs, to global mean temperatures well above 3°C.
- N_2O emissions from human activities must decline to be consistent with mitigation pathways leading to temperatures below 2°C as established by the Paris Agreement, with reductions of 20% relative to 2019 levels required by 2050. From the IPCC WGIII Figure SPM.5 or C.1.2: "There are similar reductions of non-CO2 emissions by 2050 in both types of pathways: CH4 is reduced by 45% [25–70%]; N2O is reduced by 20% [–5 to +55%]; and F-gases are reduced by 85% [20–90%]."
- The need for emissions reductions is further underscored by the fact that no technologies are available or currently in development capable of removing N_2O directly from the atmosphere (as they exist for CO_2).

How to Reduce N_2O Emissions (background information, but little is in the actual paper).

- The global annual amount of chemical N fertilizer use increased by 47.3 million metric tons of nitrogen (79%) from 59.9 million metric tons of nitrogen in 1980 to 107.2 million metric tons of nitrogen in 2020. Global manure production increased by 21.2 million metric tons of nitrogen (26.4%) from 80.2 million metric tons of nitrogen in 1980 to 101.3 million metric tons of nitrogen in 2020.
- There is no good alternative to N fertilizers that do not lead to N_2O emissions (in contrast to fossil fuel energy for which renewable energy alternatives exist that do not emit CO_2). In other words, there are no good alternatives to N fertilizer use, the primary cause of N_2O emissions.
- The food production system will always have some N_2O leakage. Therefore, the goal is to make the food system as nitrogen-efficient as possible to reduce N_2O emissions to the minimum possible.

- If N_2O emissions are not reduced, then it is necessary to deploy Carbon Dioxide Removal (CDR) technologies, to offset continued N_2O emissions and achieve net zero GHG emissions as required by the Paris Agreement).
- Increased N use efficiency (higher yields per quantity of nitrogen applied) has enabled some countries/regions to increase crop yields with smaller or no increase in N_2O emissions (Australia, Europe, Japan, Korea, USA).
- There are hotspots of excess N fertilization where the excess use leads to little or no increase in yield, and in some instances, to a decline in yield, making these regions attractive targets for reducing N inputs. For example, over-fertilization hotspots are found in the northern China Plain, Brazil, Mexico, and Thailand. These regions could reduce fertilizer use significantly without affecting their crop yields.
- Reducing the use of excess N also leads to reduced water pollution in waterways, groundwater, and reduced algae blooms in freshwater bodies and coastal zones (we showed an increase in freshwater N_2O emissions)
- Strategies for reducing N_2O emissions in the agricultural sector:
    - Precision agriculture with N fertilizers provided at the right time when plants need it, with the right quantity, and supplied at the right soil depth where will be most uptaken by plant roots.
    - Mixing or using alternate crops of the targeted crop (eg. commodity crop) and legumes to improve soil N fertility and require less N inputs as chemical fertilizer or manure.
    - Use of alternate crops with species that have natural N_2O inhibitors.
    - Long-term: to integrate genetically engineered N_2O inhibitors or N fixing symbiosis into main commodity crops.
    - Improved manure management and use.
    - Climate-smart agriculture, and more effective and holistic farming that maintains good soil health can play an important role in carbon sequestration.
    - Hydroponics and urban agriculture.
    - Reduced food waste.
    - Sources of supplemental amino acids or other non-protein N in livestock feed could reduce the need to grow as many fertilized crops for animal feed.
- Industry (e.g., nylon producers) has more direct and easier ways to mitigate N_2O emissions. The flue gases of certain industrial processes may contain very high concentrations of N_2O, which can be efficiently removed by secondary combustion or by catalytic reduction performed on this exhaust, sometimes simultaneously with measures that abate air pollution (NO_x). The Nylon industry (adipic acid production) has implemented measures since the late 1990s in Europe and North America. The technology is a bit more challenging for nitric acid production, used in fertilizer and explosives production, as flue gas concentrations are lower. Nevertheless, all plants in the European Union have been equipped over the last decade, reducing emissions from this sector by 80%. Therefore, the remaining industry elsewhere has a clear technical path to rapidly reducing emissions.
- Fertilizer consumption has decreased in Europe over the last decades, despite maintaining high agricultural output. Some of that may be a result of water protection

legislation, but also high fertilizer prices may have contributed to efforts to increase nitrogen use efficiency.

- Total anthropogenic N2O emissions from China have been decreasing since 2016, which is primarily attributed to reduced nitrogen fertilizer applications in agriculture. In 2015, the Chinese Ministry of Agriculture issued the Action Plan for Zero Growth in Fertilizer Use by 2020. Afterward, the best nitrogen management practices have been implemented to reduce fertilizer applications while maintaining crop yield. However, industrial emissions in China have been increasing strongly recently, so there is a necessity to take mitigation measures to reduce industrial N2O emissions.

Source and Contact Information

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Open Access: https://doi.org/10.5194/essd-16-2543-2024, 2024. The paper will be online accessible on 12 June 2024, 00:01 CEST.

For more resources on this release and data availability, visit Global Carbon Project https://www.globalcarbonproject.org/nitrousoxidebudget/index.htm (new link to be updated on June 12)

Emissions data and display interface with national emissions at the Global Carbon Atlas: https://globalcarbonatlas.org/

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Authors of the paper have also indicated their willingness to take media inquiries. Contact them as per regional/country relevance of your interest.