German Environment Agency

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Nitrous oxide - the underestimated greenhouse gas

Anthropogenic N_2O emissions are increasing – As a result of climate change, additional nitrous oxide is being released from natural sources

1 Climate relevance and formation of nitrous oxide

1.1 Significance as a greenhouse gas

Although the concentration of nitrous oxide (N_2O) is thousands of times lower, it has three hundred times the climate impact of CO_2. It remains in the atmosphere for over 100 years. The atmospheric concentration relevant to climate impact averaged 335.65 parts per billion (ppb) in 2022 and continues to increase by just over one ppb per year. According to the Intergovernmental Panel on Climate Change (IPCC), its share of total global anthropogenic (i.e. caused by humans or their activities) greenhouse gas emissions in 2019, converted into CO_2 equivalents, was around five percent. In short, its significance is more than relevant and is generally underestimated.

1.2 Role in the earth's natural nitrogen cycle

Nitrogen is a vital element, for example in plant growth. While 78 percent of the earth's atmosphere consists of inert, non-reactive nitrogen, reactive nitrogen essentially occurs in eight different forms. Ammonia and nitrate, for example, react with their environment when oxygen and bacteria are present. Nitrous oxide is one of the reactive nitrogens and is the only long-lived gas that sustains the greenhouse effect of the Earth's atmosphere (Figure 1).

1.3 Anthropogenic sources of nitrous oxide

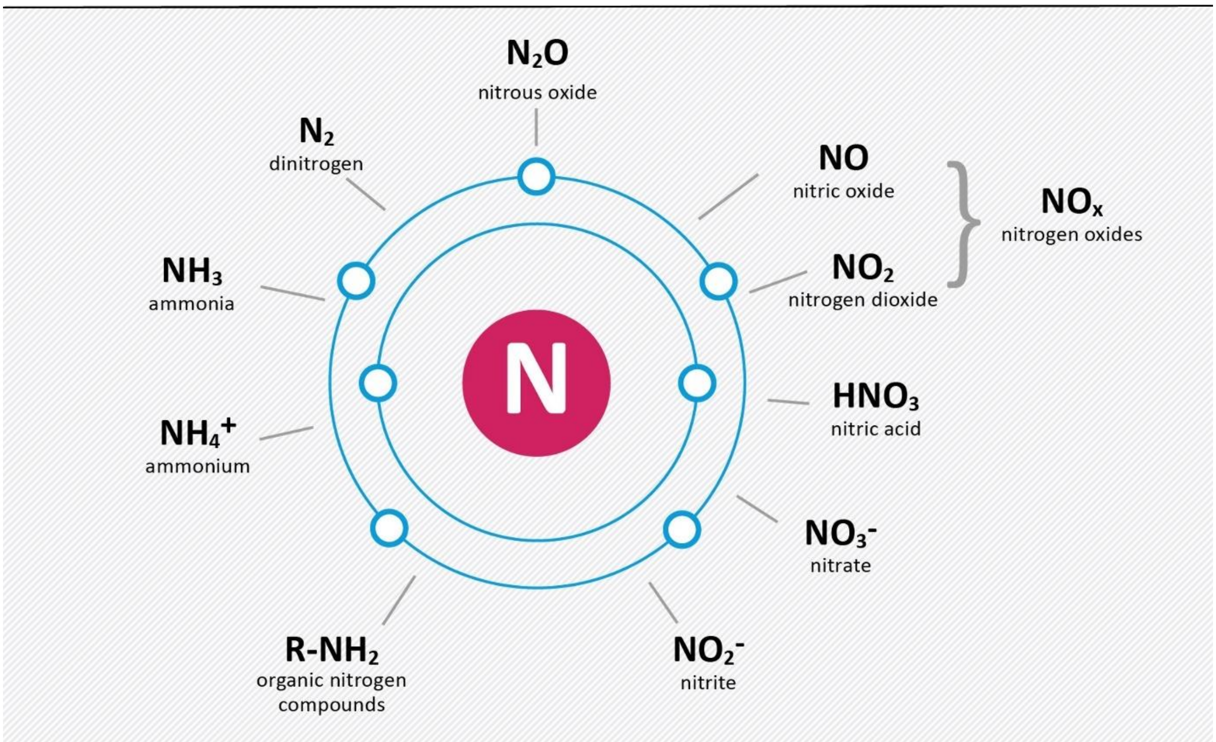
Man-made influences such as artificially produced fertilizers in agriculture, the production of acids in industry, fossil fuels, wastewater from sewage treatment plants or the burning of biomass, add nitrogen to the natural cycle and thus directly and indirectly increase nitrous oxide emissions into the atmosphere.

The additional nitrous oxide increases the climate effect of anthropogenic greenhouse gases and also the destruction of the ozone layer. Natural nitrous oxide emissions are also disrupted and, in some cases, intensified by various processes. These include climate change, the increase in CO_2 in the atmosphere and changes in land use such as deforestation.

1.4 Measurability of nitrous oxide emissions

The absolute proportion of nitrous oxide in the Earth's atmosphere can be measured very accurately. The quantification of nitrous oxide emissions, on the other hand, is complex. So-called bottom-up estimates are based on the empirical upscaling of point measurements, greenhouse gas inventories and dynamic model simulations, while top-down estimates are based on atmospheric measurements and so-called inverse models, which incorporate assumptions about the transport of air masses. While top-down calculations do not distinguish between anthropogenic and natural sources of nitrous oxide emissions, the bottom-up data is primarily used for reference on anthropogenic emissions.

Figure 1: The main forms of nitrogen in the environment



Source: own representation modified after Sutton et al. 2022, Susanne Schödel.

In accordance with international conventions, emissions are expressed in tons of nitrogen contained in nitrous oxide ("N_2O-N"). One ton of N_2O-N corresponds to 1.57 tons of nitrous oxide, and this quantity in turn corresponds to around 416 tons of CO_2 equivalents, the reference and comparative figure in the standardized greenhouse gas balances.

The current "Global N_2O Budget" of the Global Carbon Project was evaluated for the inventory of nitrous oxide emissions (Tian et al. 2023 and 2023a). It brings together all available data for anthropogenic and natural emissions at a global and regional level in a structured manner.

2 Global N_2O budget, regional trends

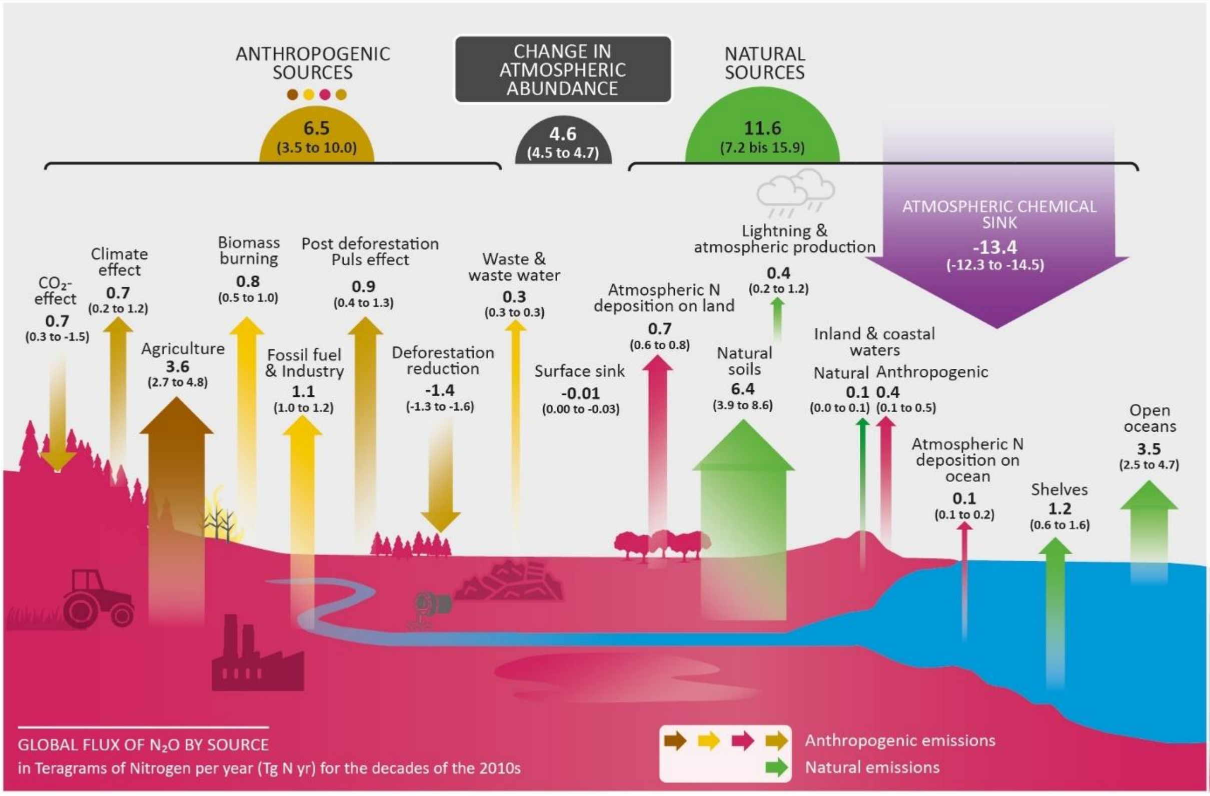
2.1 Trends in anthropogenic and natural nitrous oxide emissions

According to the Global N_2O budget for the years 2010 to 2019 (Figure 2), global N_2O emissions amounted to an average of 18.2 million tons (expressed in Teragram, Tg respectively Megaton, Mt in German language) of N_2O-N per year (bottom-up) and 17.4 Tg of N_2O-N per year (top-down). In the bottom-up calculation, the range of data sources is a minimum of 10.4 to a maximum of 25.9 Tg, for the top-down calculation 15.8 to 19.2 Tg N_2O-N per year.

In the four decades since 1980, man-made emissions have risen by almost 35 percent to 6.7 Tg N_2O-N in 2020. The main sources are artificial and animal nitrogen fertilizers in agriculture and industrial aquaculture. They lead to direct emissions at the site of use as well as indirect emissions, for example when excess nitrogen is washed out via watercourses and later turns into nitrous oxide through biogeochemical processes. The use of nitrogen in agriculture accounts for almost 60 percent of all anthropogenic nitrous oxide emissions. This is the main factor in the increasing atmospheric pollution by nitrous oxide: the other direct anthropogenic sources from industry, fossil fuels, the combustion of biomass and wastewater as well as the natural nitrous oxide fluxes have changed only slightly between 1980 and 2020.

Figure 2: Global N_2O budget 2010 to 2019

N_2O fluxes by source in Teragram (Tg) of nitrogen per year (N_2O-N). In brackets, minimum and maximum values of the respective data sources.



Source: Slightly adapted and translated presentation based on Tian et al. 2023, Susanne Schödel.

Anthropogenic emissions accounted for an estimated 36 percent of total global nitrous oxide emissions at the end of the study period, meaning that slightly less than two-thirds are produced naturally.

The main sink is the stratosphere, where secondary products of N_2O react with ozone and both are broken down as a result. Estimates based on various models and methods have been possible since the end of the 1990s and indicate that between 12.2 and 13.4 Tg N_2O-N were depleted here every year between 2000 and 2019.

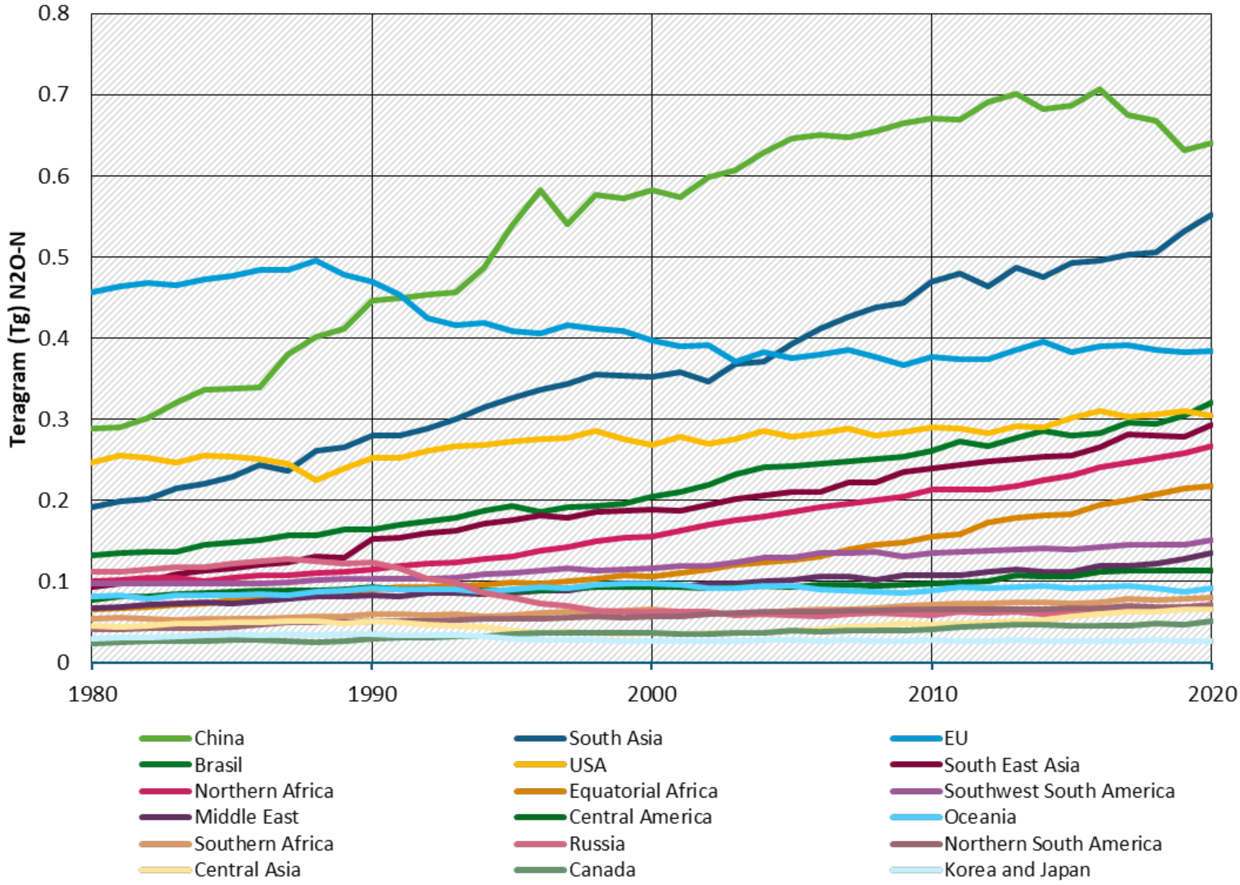
In net terms, therefore, an increasing amount of nitrous oxide remains in the atmosphere every year. For the years 1990 to 1999, it is estimated at 3.6 Tg N_2O-N, for the following decade 2000 to 2019 at 4.6 Tg, and for 2020 already at 6.4 Tg N_2O-N. This surplus quantity is distributed in the earth's atmosphere and also explains the increasing absolute proportion of N_2O.

2.1.1 Direct emissions from agriculture

The ten largest emitters from agriculture in 2020 are China with over 0.6 Tg N_2O-N, followed by South Asia, the EU, Brazil, the USA, Southeast Asia, North Africa, Equatorial Africa, Southern South America and the Middle East. In the EU and Russia, emissions from agriculture have fallen significantly since 1980: to less than 0.4 Tg and 0.1 Tg N_2O-N per year respectively. In the EU, this is mainly attributed to political measures to reduce the use of nitrogen fertilizers in agriculture, while in Russia it is due to the collapse of the agricultural cooperative system since the 1990s. From 1980 to 2020, nitrous oxide emissions from agriculture more than tripled in Equatorial Africa and Southeast Asia, and more than doubled in six regions: South Asia, North Africa, Brazil, China, Canada and the Middle East.

Figure 3: Direct anthropogenic nitrous oxide emissions from the use of nitrogen in agriculture, by region from 1980 to 2020

Direct soil emissions from fertilizers, livestock manure on pastureland, fertilizer management, aquaculture



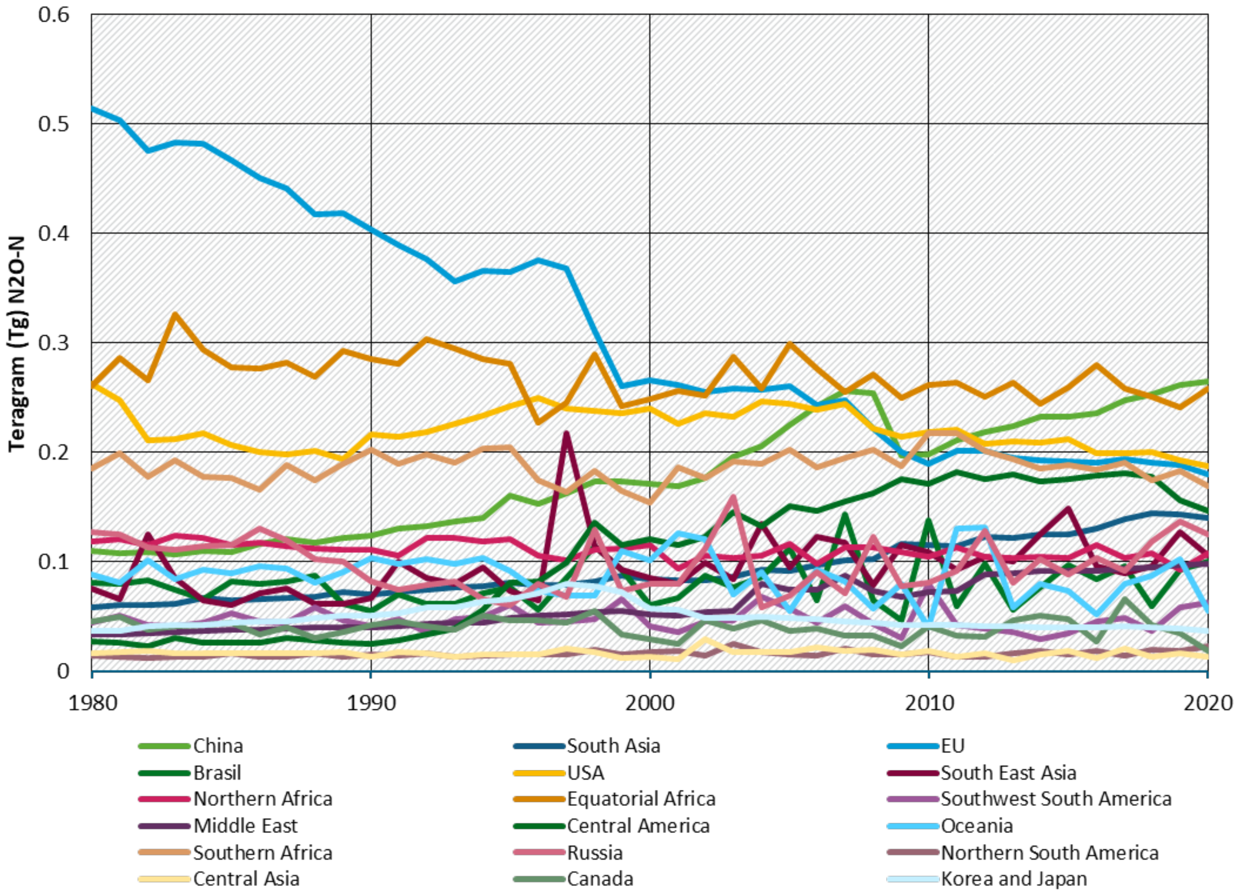
Source: own analysis based on data from Tian et al. 2023, Susanne Schödel.

2.1.2 Other direct anthropogenic nitrous oxide emissions

The second analyzed area of direct anthropogenic emissions mainly comprises emissions from fossil fuels used in road traffic, heat production and industrial processes. Another source of nitrous oxide is the production of nitric and adipic acid. These chemicals are nitrogen-containing intermediate products, for example for fertilizers, the processing of metals and plastics such as nylon. Nitrous oxide is also produced by bacterial processes in sewage treatment plants and during the combustion of biomass. This includes plant residues on harvested farmland, stoves and cooking areas in households and natural fires.

Overall, emissions from this sector only increased by around five percent between 1980 and 2020, but there are significant regional differences. Their share of anthropogenic nitrous oxide emissions was recently around 30 percent. The five largest emitters in 2020 were China and the countries in the equatorial region of Africa, each with around 0.26 Tg N_2O-N, as well as the USA, the EU and the countries in southern Africa, each with around 0.2 Tg N_2O-N. In China and South Asia, nitrous oxide emissions have more than doubled since 1980, and in Central America they have even increased fivefold. In South Asia and Central America, the most recent annual amount was just under 0.15 Tg N_2O-N. In the Middle East, emissions have almost tripled to almost 0.1 Tg N_2O-N in 2020. The significant decrease in nitrous oxide emissions in the EU from this area is mainly due to the industrial sector: Manufacturers of nitric and adipic acid use technical reduction measures on a large scale, and they are subject to the EU ETS emissions trading scheme, just like fossil fuels.

Figure 4: Direct anthropogenic nitrous oxide emissions excluding agriculture, by region from 1980 to 2020



Note: The peak in emissions in Southeast Asia in 1997 occurred during an El Niño phase due to large-scale fires, particularly in Indonesia.
Source: own analysis based on data from Tian et al. 2023, Susanne Schödel.

2.1.3 Indirect emissions and disturbed nitrous oxide flows

Indirect emissions occur, for example, when nitrogen seeps into the soil in the form of fertilizer and is transported into the oceans by watercourses. In 2020, these emissions amounted to an estimated 1.3 Tg N_2O-N. The amount has increased by over 40 percent since 1980.

The disruption of natural nitrous oxide fluxes due to climate change and rising CO_2 levels, among other things, is leading to an overall reduction in emissions. For 2020, this sink is estimated at just under -0.6 Tg N_2O-N, although the data sources here are subject to great uncertainty.

2.2 Response mechanisms in climate change

Rising temperatures due to climate change and the increasing global use of nitrogen fertilizers increase nitrous oxide emissions from the soil. Increased CO_2 concentrations in turn lead to increased plant growth and thus to more nitrogen being captured, which can then no longer be converted into nitrous oxide through bacterial processes. The interactions are multifaceted and the effects cannot be clearly quantified. However, it can be assumed that the climate changes already taking place will lead to further N_2O emissions that are not of direct anthropogenic origin but come from indirect or natural sources.

3 Important approaches to reducing anthropogenic nitrous oxide emissions

The main starting point for reducing nitrous oxide emissions are the direct anthropogenic sources from agriculture. Experts suggest closing the nitrogen cycle and avoiding losses during use in agriculture and livestock farming. In addition, they suggest considering systemic changes that reduce nitrogen losses, for example in human and animal nutrition and in the use of fertilizers. Tangible measures range from lower-protein diets for dairy and beef cattle and pigs to the more targeted use of fertilizers in arable farming, the treatment of liquid manure and special landscape management measures.

Biomass emissions can be prevented by processing rather than burning it on arable land. Biomass can be replaced by other fuels in household stoves. Natural fires can be influenced by controlled burning. An effective reduction in emissions from fossil fuels and industry is feasible through technical measures. Their introduction can be accelerated by legal requirements, international agreements and inclusion in emissions trading systems, as already in existence in the EU. Nitrous oxide emissions from wastewater can be controlled especially through certain treatment steps in multi-stage wastewater treatment plants.

4 Outlook

Nitrous oxide as a greenhouse gas should therefore not be underestimated. It is foreseeable that the absolute proportion of nitrous oxide in the atmosphere and thus its impact on the climate will continue to rise in the coming decades. This trend can be reversed if the technical and political measures that reduce nitrous oxide emissions are consistently implemented. To this end, they must become part of political action to protect the climate, which has so far focused primarily on carbon dioxide and methane.

It is important to have better and more accurate input data both for the more reliable calculation of nitrous oxide emissions and their successful reduction as well as for future developments within the context of scenarios and models. To this end, it would be necessary to conduct more and increasingly permanent measurement campaigns under quite different conditions in order to gain an even better understanding of the causes and quantities of nitrous oxide emissions.

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Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
buergerservice@uba.de
Internet: www.umweltbundesamt.de
/umweltbundesamt.de
/umweltbundesamt

Authors, Institutions

Susanne Schödel,
Susanne Schödel GmbH Environment Data

Editorial office
Department V1.1 - Climate protection
Dr. Mathias Ulrich

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