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Global N$_2$O emissions from our planet: Which fluxes are affected by man, and can we reduce these?

Søren Christensen$^1$,* and Kathrin Rousk$^1$

SUMMARY
In some places, N$_2$O emissions have doubled during the last 2-3 decades. Therefore, it is crucial to identify N$_2$O emission hotspots from terrestrial and aquatic systems. Large variation in N$_2$O emissions occur in managed as well as in natural areas. Natural unmanaged tropical and subtropical wet forests are important N$_2$O sources globally. Emission hotspots, often coupled to human activities, vary across climate zones, whereas N$_2$O emissions are most often a few kg N ha$^{-1}$ year$^{-1}$ from arable soils, drained organic soils in the boreal and temperate zones often release 20–30 kg N ha$^{-1}$ year$^{-1}$. Similar high N$_2$O emissions occur from some tropical crops like tea, palm oil and bamboo. This strong link between increased N$_2$O emissions and human activities highlight the potential to mitigate large emissions. In contrast, water where oxic and anoxic conditions meet are N$_2$O emission hotspots as well, but not possible to reduce.

INTRODUCTION
Nitrous oxide (N$_2$O) is produced by microbial processes taking place when oxic and anoxic/microaerophilic sites are close to each other. This is because oxygen is required to produce oxidized N (nitrate (NO$_3^-$) and nitrite (NO$_2^-$)) via nitrification at the same time as anoxic conditions or very low oxygen concentrations are required to reduce NO$_3^-$ or NO$_2^-$ to N$_2$O. For this reason, there is considerable spatial and temporal variability in net N$_2$O production both in terrestrial and aquatic systems. The spatial variability in soils occurs at the microscale$^1$ i.e., at distances often below 1 cm. The reduction of NO$_3^-$/NO$_2^-$ to N$_2$O is performed by denitrifying bacteria under anoxic conditions and by nitrifying bacteria under low oxygen. Denitrification is responsible for the main part of the N$_2$O production in soil above 65% water-filled pore space.$^2$

At low mineral N and high soil moisture, soil can even be a sink for atmospheric N$_2$O, with a maximum N$_2$O absorption rate for arable land across all climates of $-0.58$ kg N$_2$O-N ha$^{-1}$ month$^{-1}$. Over billions of years, microbial processes evolved to transform nitrogen (N) in the N cycle with robust feedback and controls. Over the past century, however, new agricultural practices drastically disrupted the N cycle, leading to large increases in atmospheric N$_2$O. Analysis of ice cores revealed that pre-industrial N$_2$O concentration in the atmosphere was 270 ppb, which increased to 334 ppb in 2021.$^4$ Microbial processes may ultimately restore the balance to the N cycle, but this may take decades or even centuries.$^5$

In this review, we address the marked differences in N$_2$O emissions from different surfaces of the globe (terrestrial vs. aquatic). Such a rather detailed quantitative comparison of surfaces has not been done before. This may help identify possible changes in land use practices and our impact on aquatic systems to reduce the greenhouse effect. Our aims with this review were (1) to define the range of area-specific N$_2$O emissions from various surfaces of our planet, and (2) to synthesize this information with the cover of these surfaces across the globe. We further identify the key drivers of N$_2$O emissions. Based on these aims, we identify which areas give excessively high N$_2$O emissions. In case high emissions are related to soil management or crops, this review can help in pointing to possible changes in our activities to minimize N$_2$O emissions.

OVERVIEW OF N$_2$O EMISSIONS
More than two-thirds of the N$_2$O emission of our planet originate from soil, even though land area is only about 30% of the globe (Figure 1). This is because the combined aerobic/anoxic conditions are most common in porous soil, and because of farming activities increasing nitrate concentrations - the main N substrate for N$_2$O production - in the soil environment. Technical improvements of farming practices by a global increase in the efficiency of mineral and organic N amendments and a closer integration of animal waste and crop residue management with crop production may, however, only reduce N$_2$O emission by some 10%.$^6$

As mentioned above, the highest N$_2$O production occurs where anoxic and oxic conditions occur close to each other and where a large supply of oxidized N is available (Figure 2).

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Most of the human responsibility for global N$_2$O emissions (Figure 1) comes from farmland. The high emissions from fallow land are due to the absence of crops, which reduces the absorption by plants of the inorganic N released by mineralization. Most of this farmland would have been temperate forest (Figure 2) if not affected by humans. Tropical forests often have a higher N availability than temperate forests and N$_2$O emissions are on average 40% higher in tropical than in temperate forests (Figure 2). Of the natural areas, riparian zones have the highest N$_2$O emissions, but these areas only cover a minor fraction of the land area. For instance, 8% of Denmark - assuming a 25 m riparian zone area on each side of rivers/streams. Peatland and riparian zones are wet and may have extremely high N$_2$O emissions if fed by NO$_3$-rich water from farmland. Alternatively, if these areas receive water from unfertilized areas such as forests, N$_2$O emissions would be low. This is the reason for the large variability in N$_2$O emission from such areas. The open ocean has the lowest emissions but still constitutes the main part of the aquatic emissions, making up about 1/4 of the total global N$_2$O emissions. This is because oceans constitute 2/3 of the area of the globe (Figure 1).

The first review on N$_2$O emissions described rates with a large span, from active and less active terrestrial systems between 4.6 and 0.5 kg N$_2$O-N ha$^{-1}$ year$^{-1}$, respectively. Because of the serious problems in quantifying this extremely variable activity on a spatial and temporal scale, the work done since then has then has not brought us much further. In the following, N$_2$O emissions from the various areas of the globe are synthesized and the factors driving emissions are identified. We start with the terrestrial environment with a focus on soil factors, followed by aquatic systems and forests, natural and managed, and finish with farmland.

**FACTORS THAT CONTROL N$_2$O EMISSIONS**

**Soil physics and chemistry**

**Soil compaction**

Reducing soil porosity, by even less than 10%, markedly increases N$_2$O emissions in the majority of cases. The largest relative increases are found for forests and pastures, experiencing a 5-fold and 3-fold increase, respectively. Among the factors soil bulk density, mean annual precipitation, soil total nitrogen, and soil pH, bulk density was most important in determining N$_2$O emissions; see below).

**Soil water**

Increase in precipitation led to an increase in N$_2$O emissions by an average of 55%, while decreased precipitation suppressed N$_2$O emission by 31%. In well-aerated soil, N$_2$O emissions are often highest during winter when it is cold, due to the higher soil moisture in this period. N$_2$O emissions respond positively to an increase in moisture as well as to increases in temperature due to the increase in anaerobic volume fraction. Higher moisture levels in soils lower oxygen supply and elevated temperatures increase microbial activity and therefore, oxygen demand. In rice paddies, it may be the opposite – draining during summer supplies oxygen to the otherwise anoxic environment and thereby increases N$_2$O emissions more than three times, from 0.3 to 1.0 kg N$_2$O-N ha$^{-1}$ season$^{-1}$. Finally, high soil moisture in combination with low soil mineral N may lead to soils absorbing N$_2$O from the atmosphere because of the reduction of N$_2$O into N$_2$.

**Soil warming/freezing**

N$_2$O emissions increased on average by 33% after a temperature increase of 2.3°C (range 0.2–7.5°C) covering annual mean temperatures –5.2–26°C and increases by more than 200% have occasionally been observed. Effects were highly variable across biomes, with the
strongest, positive temperature responses in shrublands, variable responses in forests and negative responses in tundra. In cold ecosys-
tems, warming may increase N2O emissions due to increases in N mineralization and often warming interacts positively with elevated
CO2 in promoting N2O release. In line with this, for croplands in China, N2O emission was highest in the subtropical compared to the
cold temperate zone, 1.7 and 0.5 kg N ha⁻¹ year⁻¹ respectively.

Freezing-thawing can lead to a marked increase in N2O emissions by up to 150% and often substantially greater for arable soils
than for forest soils. Freezing-thawing has a particularly strong impact on N2O emissions in the temperate zone because killed biomass con-
stitutes an easily decomposable organic resource, markedly increasing oxygen demand. This is not least the case in organic farming, where
much fresh organic matter is present in the topsoil. Here, annual N2O emissions could be underestimated by 17–28% if freeze-thaw periods
are ignored.

Soil acidity
The reduction of N2O into N2 by denitrifying bacteria is significantly inhibited below pH 6.8. Therefore, N2O emissions are higher at low pH
than at neutral soil pH. In accordance with this, acid rain marginally increased soil N2O emissions by 12% and liming acidic arable soils
reduce N2O emission by 20% because the enzyme N2O reductase is more active thereby increasing N2 production.

Elevated CO2
Elevated CO2 did not affect N2O emissions from grasslands or forests but significantly increased N2O emissions in croplands by 27%, 38%, or 44%. Often the effect has been associated with CO2-induced increases in soil water, dissolved organic carbon or nitrate.

Conclusions, soil physics and chemistry
Physical factors such as soil compaction, drainage of wetlands and freeze/thaw may increase N2O emissions several fold, whereas chemical
factors such as soil acidity and elevated CO2 have a minor effect. This may give hints to optimize soil management in relation to greenhouse
gas emission.

Aquatic environments
About a quarter of the total global N2O emissions originate from the oceans, which is a major natural part of the N2O output from our globe.
This is due to the large area covered by oceans, and low oxygen zones (hypoxic) that mostly occur at the coast. For hypoxic zones in the open
ocean, average N2O emission is 0.4 kg N ha⁻¹ year⁻¹ increasing to 3.1 kg N ha⁻¹ year⁻¹ in the coastal upwelling zone. There are four
minimum oxygen zones in oceans of the world where N2O production is elevated: (1) the Eastern South Pacific, (2) the Eastern Tropical North
Pacific, (3) the Arabian Sea and (4) the Bay of Bengal, in the Indian Ocean.
Estuarine environments are highly variable in N₂O emissions varying from 1.0 kg N ha⁻¹ year⁻¹ in seagrass over 0.8 kg N ha⁻¹ year⁻¹ in salt marshes to 2.1 kg N ha⁻¹ year⁻¹ in tropical mangroves.¹

Global riverine N₂O emissions are higher in farmed areas and towns than emissions in forests being 50% below the flux from farmed areas. Rates average 3.7–5.1 kg N ha⁻¹ year⁻¹ and are forecasted to increase by 2050 due to projected increases in river water NO₃⁻ that is already now on average 400, 200 and 100 percent saturated with N₂O in the subtropical, temperate and tropical climate belts, respectively.³⁵

Man-made aquatic environments including constructed wetlands have high N₂O emission rates compared to unmanaged environments, reported to be −40 to +440 kg N ha⁻¹ year⁻¹ or −0.3 to +57 kg N ha⁻¹ year⁻¹ the highest fluxes are seen in the open water without emergent vegetation. However, macrophyte growth can reduce N₂O emissions by about 60%.³⁷ Global N₂O-N emissions from aquaculture in 2009 were estimated to be 0.92 kg N ha⁻¹ year⁻¹ and it is expected to increase 4 times before 2030.⁴⁰

Conclusions, aquatic environments
Even though aquatic environments contribute significantly to global N₂O emissions, the largest fraction of these is from natural processes and environments whose conditions (i.e., oxygen availability) are conducive for high N₂O production and emission. Nonetheless, aquaculture with relatively high N₂O emissions can be managed.

Farms: Natural and managed

Forest soils in natural tropical and subtropical areas are responsible for 40% of the total N₂O emission from terrestrial systems (Figure 1B). Tropical forest soils of the humid type may emit between 0.5 and 2.6 kg N₂O-N ha⁻¹ year⁻¹ at low or high fertility, respectively.³⁴ This is because wet forests in these regions cover 10–12% of the global land area. They are often nutrient rich, and the mix of oxic and anoxic conditions with easy access to nitrate stimulates N₂O production.

Even though thinning of even-aged forests increased soil NO₃⁻ by 12%, it did not significantly affect N₂O emissions.⁴² Right after thinning, N₂O emissions almost doubled but the effect diminished with time.⁴³ One year after forest clear-cut, N₂O was taken up by the ground during summer on mineral soil as well as on peat in Finland.⁴⁴ Drainage in the boreal zone mediates large N₂O emissions from peatlands (26 kg N ha⁻¹ year⁻¹)⁴⁵ but less for forests on organic soil (4.5 kg N₂O-N ha⁻¹ year⁻¹).⁴⁶

In temperate areas, highest fluxes originate from organic soils. Raising of forest (afforestation) on farmland on organic soils in Sweden may result in 19 kg release of N₂O-N ha⁻¹ year⁻¹ but no such effect was seen in Scotland,⁴⁸ and much less from a drained alder forest (7–9 kg N₂O-N ha⁻¹ year⁻¹).⁴⁹,⁵⁰

For unmanaged or cultivated tropical Savannas, emission was on average 0.1 kg N₂O-N ha⁻¹ month⁻¹, whereas seasonally wet tropical systems may release more than 20 times those rates (up to 2.5 kg N₂O-N ha⁻¹ month⁻¹).⁵¹ Mixed peat swamp forests in the tropics release 0.7 kg N ha⁻¹ year⁻¹.⁵² Tropical secondary forest in Cameroon gives 2.2, whereas unfertilized crop and cacao agroforestry only releases half of that: 1.0 and 1.4 kg N₂O-N ha⁻¹ year⁻¹.⁵³ In subtropical China, a bamboo forest emitted about the same amount of N₂O as an evergreen forest (8.7 and 7.2 kg N₂O ha⁻¹ year⁻¹), respectively. However, the intensively managed bamboo forest (with tillage, fertilizer) released about the double amount of N₂O (15.8 kg N₂O ha⁻¹ year⁻¹).⁵⁴

Besides management type, the age of pastures and forests can make a difference in N₂O emissions. For instance, young pastures of 1–3 years age had higher N₂O emissions than the original forest (3.1–5.1 kg N ha⁻¹ year⁻¹) but older pastures of 6 years or more had lower emissions (0.1–0.4 kg N ha⁻¹ year⁻¹).⁵⁵

Conclusions, forests
One-third of the total global N₂O emission comes from forests and most of this from wet organic soils in the tropics. We have to live with this enormous but natural emission. These areas produce much of the oxygen we have and are basis for much of the global biodiversity and are crucial for the global climate system. Forests like fast-growing bamboo may release very high amounts of N₂O and such areas should not increase for the sake of greenhouse gas emission.

Farming
In general, N₂O emissions from farmed soils have increased during the last decades. With China as example, N₂O emission has more than doubled, from 0.5 to 1.1 Tg N year⁻¹ between 1980 and 2005,⁵₆ and probably has increased since these last assessments.

N₂O emissions from arable soils in temperate Europe are very similar to arable soils in China, and in Canada between 2 and 5 kg N₂O-N ha⁻¹ year⁻¹, unusually above this.⁵₇ For sub-boreal European arable soils, however, N₂O emissions vary in a much wider range between 0 and 27 kg N₂O-N ha⁻¹ year⁻¹ due to the very high moisture in these areas.⁵₇

In the tropics, farmland N₂O emissions were estimated in three African countries to 0.6–0.8 kg N₂O-N ha⁻¹ year⁻¹; in six Asian countries to 0.2–11.2 kg N₂O-N ha⁻¹ year⁻¹; in all of Australia 1.3 and in three American countries 1.4–3.8 kg N₂O-N ha⁻¹ year⁻¹.⁵₈ Very high N₂O emissions around 20 kg N ha⁻¹ year⁻¹ and above occur under certain tropical crops as well as from drained organic soils, see below. Comparing cropping systems in the tropics to forests, they release 0.6–2.7 kg N₂O-N ha⁻¹ year⁻¹ and forests 0.4–0.8 kg N₂O-N ha⁻¹ year⁻¹, similar to agroforestry (0.1–1.1 kg N₂O-N ha⁻¹ year⁻¹). Hence, the introduction of crops in forestry may markedly reduce N₂O emissions compared to ordinary farming.⁶²
Changing forested peatlands into farming in the Nordic countries increased N₂O emissions from 2.0 to 9.9 kg N ha⁻¹ year⁻¹. For mineral soil, N₂O emissions are normally lower than for organic soils when converting forests to farmland, estimated to be 0.25 to 2.2 kg N₂O-N ha⁻¹ year⁻¹.

Crops
Not just soil characteristics, but also the type of crop that is grown can lead to large differences in N₂O emissions. For instance, root vegetables (radish, potato) emit 1.3; stems (broccoli, cauliflower, celery, asparagus) emit 1.7; fruits (tomato, cucumber, pepper) emit 2.9; bulbs (onion) emit 3.4 and leafy vegetables (lettuce, spinach etc.) emit 3.9 kg N₂O-N ha⁻¹ season⁻¹.

Some crops increase N₂O emissions above the 2–5 kg N ha⁻¹ year⁻¹ mentioned above. One example is tea, reported to give 5.4 kg N ha⁻¹ year⁻¹ or 24.3 kg N ha⁻¹ year⁻¹. Another example is palm oil showing N₂O emissions of up to 18 kg N ha⁻¹ year⁻¹. This is reflected in extremely high average N₂O emissions in e.g., a country like Malaysia of 11.3 kg N ha⁻¹ year⁻¹ from farmland because this country grows a lot of palm oil trees. Another reason for high N₂O emissions is crops harvested before maturity that leave large amounts of mineral N in the soil potentially being a source of N₂O. Vegetable production in greenhouses often gets excessive amounts of N fertilizer, above 1500 kg N ha⁻¹ year⁻¹, resulting in annual mean soil N₂O emission of around 12.0 kg N₂O-N ha⁻¹ year⁻¹. Chinese orchards naturally release 1.96 kg N₂O ha⁻¹ year⁻¹, but when adding 300 kg N from fertilizer, N₂O release increases to 4.5 and 6.2 kg N ha⁻¹ year⁻¹. Particularly tropical orchards release much N₂O. Fruit orchards go from slightly negative N₂O emissions to release of 26 kg N ha⁻¹ season⁻¹ or year⁻¹. However, greenhouse gas (GHG) emission was reduced by 28–35% by combined applications of organic and synthetic N sources, relative to synthetic N alone.

Carbon sequestration
Returning of straw and other crop residues to the soil and covering crops are all ways to sequester carbon in the soil to counteract the effect of the increase in the greenhouse gas CO₂ in the atmosphere. However, in most cases, cover crops enhance N₂O emissions and tillage interacts with crop residues in their effects on N₂O emissions. In direct drilled and reduced tillage soils crop residues give a 39% and 9% reduction in N₂O emission, whereas for conventional tillage, N₂O emission increased by 35% with crop residues. Returning crop residues, N₂O release was reduced by 27% or unaffected for paddy soils, whereas N₂O emission was enhanced by 17% or 24% for upland soils. Similar to this, straw return reduced N₂O emissions from paddy soils that becomes more anoxic, preventing production of nitrate, whereas straw addition to upland soils may form anoxic microsites in the otherwise oxic environment thereby increasing N₂O formation.

However, about 10% of the positive effect of carbon sequestration on the CO₂ budget of the atmosphere was eliminated by an increase in N₂O emission in European grasslands.

In arable crop rotations with clover-grass and cover crops, N₂O emission was 2.9 kg N ha⁻¹ year⁻¹. Removing clover-grass, cover crops and crop residues, and returning it the following spring after digestion gives 1.8 kg N₂O-N ha⁻¹ year⁻¹ or a 38% reduction because crop N uptake is efficient during spring as opposed to late autumn/winter. However, postharvest N₂O emissions from crop residues was the same for legumes as for non-legumes. Hence, the use of crops and cover crops need to be optimized to promote mineralization at the same time as crop N uptake to avoid excessive formation of N₂O.

Drainage, moisture
Wet soils most often have a high content of organic matter due to the slow decomposition of soil organic matter because of lack of oxygen. When such soils are drained for cultivation, the increased oxygen in otherwise anoxic soil can result in a large increase in N₂O emissions of up to 24.2 ± 5.1 kg N₂O-N ha⁻¹ year⁻¹ in 14 studies from Europe and New Zealand. In the same way summer drainage of rice paddies in China increased N₂O emissions from 1.0 to 2.5 kg N ha⁻¹ year⁻¹. Drainage of organic soils and peatland in Finland increased N₂O emissions from below 0.2 kg N ha⁻¹ year⁻¹ to 3.7 or 8.5 kg N ha⁻¹ year⁻¹ for bare soil or grassland, respectively. Midsummer drainage of rice paddies also results in increased N₂O emissions from 2.2 to 2.8 kg N₂O-N ha⁻¹ year⁻¹. A summary from 110 studies of lowland peatland says that drainage increased N₂O emissions and naturally drier peats release more N₂O than wetter ones.

In contrast to the organic soils of high moisture and N₂O fluxes mentioned above, semiarid areas of Colorado (USA), Saskatchewan (Canada), inner Mongolia (China) and Victoria (Australia) gave much lower N₂O emissions of 0.19 ± 0.03; 0.06 ± 0.05; 0.34 ± 0.08; 0.32 ± 0.13 kg N ha⁻¹ year⁻¹, respectively.

Tillage
In general, no till or low tillage increases N₂O emissions compared to conventional tillage. Soil moisture affects the dependence of N₂O flux on tillage. On average the annual effect of no-till on N₂O emissions with good, medium and poor aeration was a 0.06 kg N ha⁻¹ reduction, an 0.12 kg N ha⁻¹ increase, and a 2 kg N ha⁻¹ increase, respectively. For rice paddies with normal fertilization, no till gives 7.4 kg N₂O-N ha⁻¹ year⁻¹ and conventional till gives 5.6 kg N₂O-N ha⁻¹ year⁻¹ or 33% less N₂O. With no fertilizer, there is no difference between no till and conventional tillage giving 0.8 and 0.6 kg N₂O-N ha⁻¹ year⁻¹, respectively. For arable farming on well-drained soils a comparison of direct drilling (DD), reduced tillage (RT) and conventional tillage (CT) gives overall N₂O emissions of 27 and 26% lower in DD and RT, respectively, compared to CT. Replacing tillage with pesticides to keep down weeds resulted in a doubling of N₂O emissions. To conclude, reducing tillage often promotes N₂O emissions during wet/moist periods, an effect not seen on well-drained soil.
Effect of soil organism and grazers

N₂O concentration in soil air increased by 20% in the presence of earthworms, with the endogeic type of worms having the largest effect. The effects of earthworms on N₂O emissions can range from a 20% reduction to 13.4 times increase. The increase in N₂O emission is probably related to conditions in the earthworm gut being wet and rich in nutrients, whereas the decrease in N₂O emission relates to aeration of soil as a result of the worms’ movements. Research into e.g., the effects of mycorrhiza on N₂O emissions is sparse. One study, however, showed that arbuscular mycorrhiza can reduce N₂O emissions up to 10 times due to efficient competition against other soil organisms for inorganic N, which decreases the substrate for N₂O production.

Grazing in China on the Tibetan plateau increased N₂O emissions by 35 or 62% at light and intense grazing, respectively, whereas heavy grazing on a degraded soil led to a 30% reduction in N₂O emissions. In New Zealand, N₂O fluxes were highest in dairy-grazed pastures (10–12 kg N₂O-N ha⁻¹ year⁻¹), intermediate in sheep-grazed pastures, (4–6 kg N₂O-N ha⁻¹ year⁻¹), and lowest in un-grazed pasture soils (1–2 kg N₂O-N ha⁻¹ year⁻¹). Variation in food for grazers may affect their urine giving differences in N₂O emission: Animals fed with rape vs. fed with ryegrass/white clover released respectively 1.54% vs. 1.20% of the supplied urea-N as N₂O-N. Not surprisingly, fertilizers containing nitrogen lead to higher N₂O emissions than fertilizers containing urea, for example. Controlled, slow-release urea gives about 25% less N₂O emission than ordinary urea. The highest N₂O emissions from a grassland due to N-fertilization came from urine (10x increase), followed by slurry (9x increase), dung (8x increase), NH₄SO₄ (6x increase) NH₄NO₃ (4x increase) and finally, urea (3x increase). Solid manure leads to lower N₂O emissions (0.99 kg N₂O-N·ha⁻¹·year⁻¹) than liquid manure (2.83 kg N₂O-N·ha⁻¹·year⁻¹) or mineral fertilizer (2.82 kg N₂O-N·ha⁻¹·year⁻¹).

Nitrogen fertilizer

Nitrogen fertilizer rate is the best single predictor of N₂O emissions from agricultural soils based on 75 publications representing 338 observations. Globally across all ecosystems, N addition increased N₂O emission by 216%. Annual addition of fertilizer of 35–557 kg N/ha gave a mean increase in emissions of 2.02 ± 0.28 g N₂O-N·ha⁻¹·day⁻¹ compared to unfertilized. N₂O emissions increased abruptly at N input rates above plant uptake capacity. Hence, in order to reduce N₂O emissions, fertilizer N applications should be kept within safe limits. For unfertilized maize and wheat N₂O emission was 0.7 kg N ha⁻¹ season⁻¹ compared to 2.1 kg N ha⁻¹ season⁻¹ for fertilized maize and wheat. For maize, rice, and wheat, N₂O emission was 2.0–1.4–1.6 kg N ha⁻¹ season⁻¹, but could be reduced to 1.7–2.1–2.4 kg N ha⁻¹ season⁻¹ with a 20% reduction in N application. Maize production in China amended with 156 kg N ha⁻¹ (average), N₂O emission was 1.1–1.2 kg N ha⁻¹ season⁻¹ whereas 257 kg N ha⁻¹ (average) gave 1.9–2.1 kg N ha⁻¹ season⁻¹. Rice paddies receiving up to 125 kg N ha⁻¹ had no increase in N₂O emission, e.g., 0.5 kg N₂O ha⁻¹ season⁻¹, with increased N-load up to 250 kg N ha⁻¹ N₂O emission increased to 1.5 kg N₂O ha⁻¹ season⁻¹. Fertilized orchards released double (3.6 kg N₂O-N ha⁻¹·year⁻¹) compared to unfertilized orchards (1.96 kg N₂O-N·ha⁻¹·year⁻¹).

Application of manure increased N₂O emissions and may lead to very high emissions of up to 15 kg N₂O-N·ha⁻¹·year⁻¹. Anoxic digestion of manure may also increase N₂O emission compared to original manure following field application due to the increase in soil nitrate. There is a discrepancy among studies whether manure increases N₂O emissions more than synthetic fertilizer or if these amendments have the same effect on N₂O emissions. A positive interaction between manure and artificial fertilizer on N₂O emissions has been noted in the sense that manure amendment increases emission from fertilizer. Different manures vary in their effect on N₂O emission with animal slurries giving a 2.2 kg N ha⁻¹ season⁻¹ increase, solid manure composts and crop residues resulting in a 1.1 kg N₂O-N·ha⁻¹·season⁻¹ increase and composts mediating 0.5 kg N₂O-N·ha⁻¹·season⁻¹ more than control. Hence, application of inorganic N often increases N₂O emissions from below 1 kg N₂O-N·ha⁻¹·year⁻¹ by further 1–2 kg N₂O-N·ha⁻¹·year⁻¹. Application of wet organic fertilizer like slurry may increase emissions even further.

Inhibitors and stimulators of N₂O emissions

Several reviews describe how nitrification inhibitors reduce N₂O emissions from farmed soils. Among these, 2-chloro-6-(trichloromethyl)pyridine (nitrarpyrin), dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) are the most commonly used. Reductions of about 1/3 or up to 1/2 have been measured due to these inhibitors. However, the use of nitrification inhibitors for this purpose has also resulted in contamination of waterways with the inhibitors and production of smog has also been reported. Urease inhibitors have been reported to either decrease N₂O emissions or have no effect on N₂O emissions, and this discrepancy may be related to soil pH.

Several reviews describe how biochar application reduce N₂O emissions in farmland, and in greenhouses but the effect seems to be rather short-lasting and inconsistent.

Conclusions, farming

Global farm N₂O emissions have increased in the last decades, mainly due to increased application of mineral N fertilizer. One problem is that N fertilizers are relatively cheap, and high N amendments result in relatively high soil nitrate when no crop is present to take up the fertilizer. Given the factors conducive to N₂O production, drained organic wetlands should not be farmed, and semi-arid farming loses less N as N₂O than the aforementioned areas with a similar yield for the same cereal crops.

Some crops release much N₂O during their growth, in particular orchards, tea and palm oil. It is not realistic to avoid growth of vegetables and tea, but we should invest in producing oil from plants other than palm, e.g., rape and sunflower.
Conclusions and recommendations

Biological N₂O release per area is extremely variable across the globe, ranging from less than 0.1 kg N₂O-N ha⁻¹ year⁻¹ from oceans to 8 kg N₂O-N ha⁻¹ year⁻¹ for riparian areas. However, given the large global cover of oceans—almost 70%—, oceans contribute 20% to the global N₂O emissions, whereas riparian areas covering only a small part of the contribution of rivers, reservoirs, lakes, estuaries and coastal zones, contribute less than 3% of the global N₂O emissions.

Even though farmland is responsible for only just above 20% of the biological N₂O emissions from our globe, this is the part we can manage and should focus on if we want to reduce N₂O emissions. In contrast, almost half of the global N₂O emissions come from natural sources, and we cannot do much about that. But still, farming activities are the background for the 25% increase in atmospheric N₂O since the middle of the 19th century. The non-biological N₂O emissions from fossil fuels are just below one-fifth of the global emissions and were not the topic of this review. To reduce N₂O emissions from our planet, we should reduce the amount of inorganic fertilizer and avoid farming wet organic soils. While the evidence is there, it is an open question if an ambitious 50% reduction in N₂O emissions from farmed land giving a 10% reduction in N₂O emissions will be a marked improvement of the greenhouse gas balance of our planet.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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