

## Review

Global N<sub>2</sub>O emissions from our planet: Which fluxes are affected by man, and can we reduce these?Søren Christensen<sup>1,\*</sup> and Kathrin Rousk<sup>1</sup>

## SUMMARY

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

## INTRODUCTION

Nitrous oxide (N<sub>2</sub>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<sub>3</sub><sup>-</sup>) and nitrite (NO<sub>2</sub><sup>-</sup>)) via nitrification at the same time as anoxic conditions or very low oxygen concentrations are required to reduce NO<sub>3</sub><sup>-</sup> or NO<sub>2</sub><sup>-</sup> to N<sub>2</sub>O. For this reason, there is considerable spatial and temporal variability in net N<sub>2</sub>O production both in terrestrial and aquatic systems. The spatial variability in soils occurs at the microscale<sup>1</sup> i.e., at distances often below 1 cm. The reduction of NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup> to N<sub>2</sub>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<sub>2</sub>O production in soil above 65% water-filled pore space.<sup>2</sup> At low mineral N and high soil moisture, soil can even be a sink for atmospheric N<sub>2</sub>O, with a maximum N<sub>2</sub>O absorption rate for arable land across all climates of -0.58 kg N<sub>2</sub>O-N ha<sup>-1</sup> month<sup>-1</sup>.<sup>3</sup>

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<sub>2</sub>O. Analysis of ice cores revealed that pre-industrial N<sub>2</sub>O concentration in the atmosphere was 270 ppb, which increased to 334 ppb in 2021.<sup>4</sup> Microbial processes may ultimately restore the balance to the N cycle, but this may take decades or even centuries.<sup>5</sup>

In this review, we address the marked differences in N<sub>2</sub>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<sub>2</sub>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<sub>2</sub>O emissions. Based on these aims, we identify which areas give excessively high N<sub>2</sub>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<sub>2</sub>O emissions.

OVERVIEW OF N<sub>2</sub>O EMISSIONS

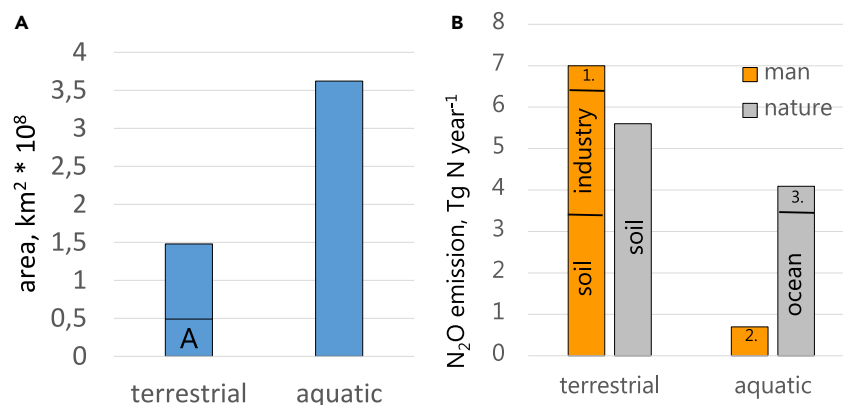
More than two-thirds of the N<sub>2</sub>O emission of our planet originate from soil, even though land area is only about 30% of the globe (Figure 1). This is because the combined aerobic/anoxic conditions are most common in porous soil, and because of farming activities increasing nitrate concentrations - the main N substrate for N<sub>2</sub>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<sub>2</sub>O emission by some 10%.<sup>6</sup>

As mentioned above, the highest N<sub>2</sub>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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**Figure 1. Terrestrial and aquatic areas on the globe and N<sub>2</sub>O emissions from these areas, affected by human activity or natural**

(A) Area covered by land and water on the globe. "A" is fraction of terrestrial area being farmland (37%).

(B) The two realms of the globe have different intensities of N<sub>2</sub>O production. Man-made terrestrial emissions labeled "soil" covers farmland and manure management; "industry" includes fossil fuel handling, biomass burning and N deposition. "1" is climate effects such as elevated temperature and CO<sub>2</sub>. Man-made aquatic emissions ("2") covers aquaculture, N pollution of inland waters, coastal zones and estuaries. Subtropical and tropical forests together emit about half of the natural, terrestrial N<sub>2</sub>O emissions. Natural aquatic emissions that are not ocean ("3") are inland waters, coastal zones, estuaries and lightning, data accessed March–September 2023.<sup>7,8</sup>

Most of the human responsibility for global N<sub>2</sub>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<sub>2</sub>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<sub>2</sub>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<sub>2</sub>O emissions if fed by NO<sub>3</sub><sup>-</sup> rich water from farmland. Alternatively, if these areas receive water from unfertilized areas such as forests, N<sub>2</sub>O emissions would be low. This is the reason for the large variability in N<sub>2</sub>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<sub>2</sub>O emissions. This is because oceans constitute 2/3 of the area of the globe (Figure 1).

The first review on N<sub>2</sub>O emissions described rates with a large span, from active and less active terrestrial systems between 4.6 and 0.5 kg N<sub>2</sub>O -N ha<sup>-1</sup> year<sup>-1</sup>, respectively.<sup>12</sup> Because of the serious problems in quantifying this extremely variable activity on a spatial and temporal scale, the work done since then has not brought us much further. In the following, N<sub>2</sub>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<sub>2</sub>O EMISSIONS

### Soil physics and chemistry

#### Soil compaction

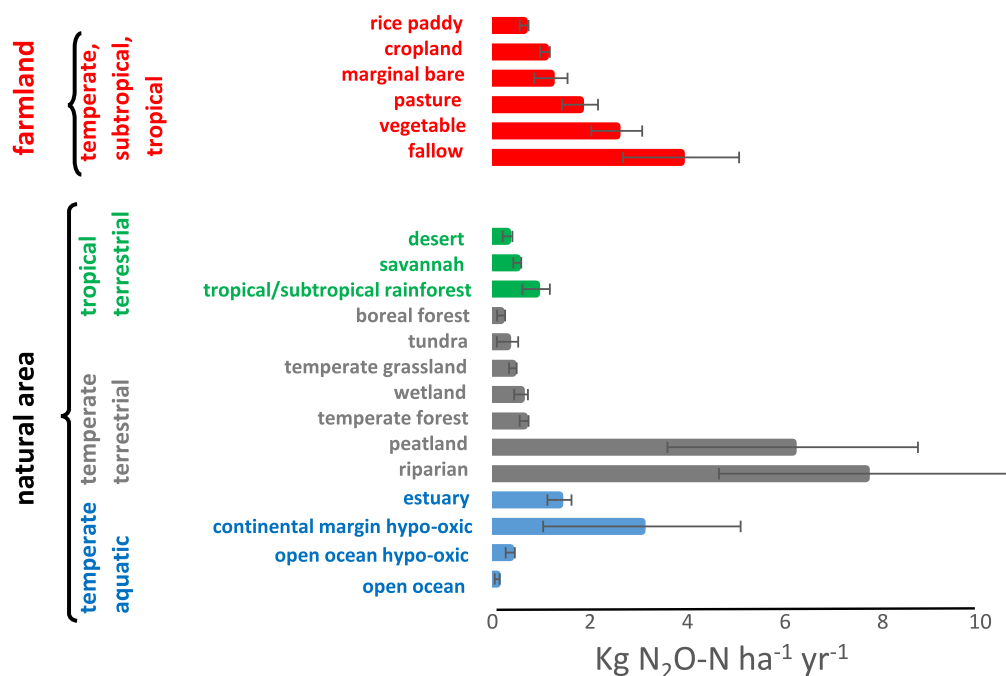
Reducing soil porosity, by even less than 10%, markedly increases N<sub>2</sub>O emissions in the majority of cases.<sup>13</sup> The largest relative increases are found for forests and pastures, experiencing a 5-fold and 3-fold increase, respectively.<sup>14</sup> Among the factors soil bulk density, mean annual precipitation, soil total nitrogen, and soil pH, bulk density was most important in determining N<sub>2</sub>O emissions<sup>15</sup>; see below).

#### Soil water

Increase in precipitation led to an increase in N<sub>2</sub>O emissions by an average of 55%, while decreased precipitation suppressed N<sub>2</sub>O emission by 31%.<sup>16</sup> In well-aerated soil, N<sub>2</sub>O emissions are often highest during winter when it is cold, due to the higher soil moisture in this period.<sup>17</sup> N<sub>2</sub>O emissions respond positively to an increase in moisture<sup>13,18</sup> as well as to increases in temperature<sup>18</sup> 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<sub>2</sub>O emissions more than three times, from 0.3 to 1.0 kg N<sub>2</sub>O -N ha<sup>-1</sup> season<sup>-1</sup>.<sup>19,20</sup> Finally, high soil moisture in combination with low soil mineral N may lead to soils absorbing N<sub>2</sub>O from the atmosphere because of the reduction of N<sub>2</sub>O into N<sub>2</sub>.<sup>3</sup>

#### Soil warming/freezing

N<sub>2</sub>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<sup>16</sup> and increases by more than 200% have occasionally been observed.<sup>21</sup> Effects were highly variable across biomes, with the



**Figure 2.** N<sub>2</sub>O emissions (kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>, average and S.E.) intensities at various areas of the globe, divided into farmland (top) and natural areas (bottom)<sup>9–11</sup>

strongest, positive temperature responses in shrublands, variable responses in forests and negative responses in tundra.<sup>16</sup> In cold ecosystems, warming may increase N<sub>2</sub>O emissions due to increases in N mineralization<sup>22</sup> and often warming interacts positively with elevated CO<sub>2</sub> in promoting N<sub>2</sub>O release.<sup>23</sup> In line with this, for croplands in China, N<sub>2</sub>O emission was highest in the subtropical compared to the cold temperate zone, 1.7 and 0.5 kg N ha<sup>-1</sup> year<sup>-1</sup> respectively.<sup>15</sup>

Freezing-thawing can lead to a marked increase in N<sub>2</sub>O emissions<sup>24</sup> - by up to 150%<sup>13,25,26</sup> and often substantially greater for arable soils than for forest soils.<sup>27</sup> Freezing-thawing has a particularly strong impact on N<sub>2</sub>O emissions in the temperate zone because killed biomass constitutes 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 N<sub>2</sub>O emissions could be underestimated by 17–28% if freeze-thaw periods are ignored.<sup>13</sup>

### Soil acidity

The reduction of N<sub>2</sub>O into N<sub>2</sub> by denitrifying bacteria is significantly inhibited below pH 6.8. Therefore, N<sub>2</sub>O emissions are higher at low pH than at neutral soil pH<sup>28–30</sup>). In accordance with this, acid rain marginally increased soil N<sub>2</sub>O emissions by 12%<sup>31</sup> and liming acidic arable soils reduce N<sub>2</sub>O emission by 20%<sup>32</sup> because the enzyme N<sub>2</sub>O reductase is more active thereby increasing N<sub>2</sub> production.

### Elevated CO<sub>2</sub>

Elevated CO<sub>2</sub> did not affect N<sub>2</sub>O emissions from grasslands<sup>23,33</sup> or forests<sup>23</sup> but significantly increased N<sub>2</sub>O emissions in croplands by 27%,<sup>23</sup> 38%,<sup>34</sup> or 44%.<sup>30</sup> Often the effect has been associated with CO<sub>2</sub>-induced increases in soil water, dissolved organic carbon or nitrate.<sup>30</sup>

## Conclusions, soil physics and chemistry

Physical factors such as soil compaction, drainage of wetlands and freeze/thaw may increase N<sub>2</sub>O emissions several fold, whereas chemical factors such as soil acidity and elevated CO<sub>2</sub> 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 N<sub>2</sub>O emissions originate from the oceans, which is a major natural part of the N<sub>2</sub>O 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 N<sub>2</sub>O emission is 0.4 kg N ha<sup>-1</sup> year<sup>-1</sup> increasing to 3.1 kg N ha<sup>-1</sup> year<sup>-1</sup> in the coastal upwelling zone.<sup>10,35</sup> There are four minimum oxygen zones in oceans of the world where N<sub>2</sub>O 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.<sup>36</sup>

Estuarine environments are highly variable in  $\text{N}_2\text{O}$  emissions varying from  $1.0 \text{ kg N ha}^{-1} \text{ year}^{-1}$  in seagrass over  $0.8 \text{ kg N ha}^{-1} \text{ year}^{-1}$  in salt marshes to  $2.1 \text{ kg N ha}^{-1} \text{ year}^{-1}$  in tropical mangroves.<sup>11</sup>

Global riverine  $\text{N}_2\text{O}$  emissions are higher in farmed areas and towns than emissions in forests being 50% below the flux from farmed areas. Rates average  $3.7\text{--}5.1 \text{ kg N ha}^{-1} \text{ year}^{-1}$  and are forecasted to increase by 2050 due to projected increases in river water  $\text{NO}_3^-$  that is already now on average 400, 200 and 100 percent saturated with  $\text{N}_2\text{O}$  in the subtropical, temperate and tropical climate belts, respectively.<sup>37</sup>

Man-made aquatic environments including constructed wetlands have high  $\text{N}_2\text{O}$  emission rates compared to unmanaged environments, reported to be  $-40$  to  $+440 \text{ kg N ha}^{-1} \text{ year}^{-1}$ ,<sup>38</sup> or  $-0.3$  to  $+57 \text{ kg N ha}^{-1} \text{ year}^{-1}$ ,<sup>39</sup> the highest fluxes are seen in the open water without emergent vegetation. However, macrophyte growth can reduce  $\text{N}_2\text{O}$  emissions by about 60%.<sup>39</sup> Global  $\text{N}_2\text{O}$ -N emissions from aquaculture in 2009 were estimated to be  $0.92 \text{ kg N ha}^{-1} \text{ year}^{-1}$  and it are expected to increase 4 times before 2030.<sup>40</sup>

### Conclusions, aquatic environments

Even though aquatic environments contribute significantly to global  $\text{N}_2\text{O}$  emissions, the largest fraction of those is from natural processes and environments whose conditions (i.e., oxygen availability) are conducive for high  $\text{N}_2\text{O}$  production and emission. Nonetheless, aquaculture with relatively high  $\text{N}_2\text{O}$  emissions can be managed.

### Forests: Natural and managed

Forest soils in natural tropical and subtropical areas are responsible for 40% of the total  $\text{N}_2\text{O}$  emission from terrestrial systems (Figure 1B). Tropical forest soils of the humid type may emit between  $0.5$  and  $2.6 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$  at low or high fertility, respectively.<sup>41</sup> 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  $\text{N}_2\text{O}$  production.

Even though thinning of even-aged forests increased soil  $\text{NO}_3^-$  by 12%, it did not significantly affect  $\text{N}_2\text{O}$  emissions.<sup>42</sup> Right after thinning,  $\text{N}_2\text{O}$  emissions almost doubled but the effect diminished with time.<sup>43</sup> One year after forest clear-cut,  $\text{N}_2\text{O}$  was taken up by the ground during summer on mineral soil as well as on peat in Finland.<sup>44</sup> Drainage in the boreal zone mediates large  $\text{N}_2\text{O}$  emissions from peatlands ( $26 \text{ kg N ha}^{-1} \text{ year}^{-1}$ )<sup>45</sup> but less for forests on organic soil ( $4.5 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ ).<sup>46</sup>

In temperate areas, highest fluxes originate from organic soils. Raising of forest (afforestation) on farmland on organic soils in Sweden may result in  $19 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ <sup>47</sup> but no such effect was seen in Scotland,<sup>48</sup> and much less from a drained alder forest ( $7\text{--}9 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ ).<sup>49,50</sup>

For unmanaged or cultivated tropical Savannas, emission was on average  $0.1 \text{ kg N}_2\text{O-N ha}^{-1} \text{ month}^{-1}$ , whereas seasonally wet tropical systems may release more than 20 times those rates (up to  $2.5 \text{ kg N}_2\text{O-N ha}^{-1} \text{ month}^{-1}$ ).<sup>51</sup> Mixed peat swamp forests in the tropics release  $0.7 \text{ kg N ha}^{-1} \text{ year}^{-1}$ .<sup>52</sup> Tropical secondary forest in Cameroon gives 2.2, whereas unfertilized crop and cacao agroforestry only releases half of that:  $1.0$  and  $1.4 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ .<sup>53</sup> In subtropical China, a bamboo forest emitted about the same amount of  $\text{N}_2\text{O}$  as an evergreen forest ( $8.7$  and  $7.2 \text{ kg N}_2\text{O ha}^{-1} \text{ year}^{-1}$ , respectively). However, the intensively managed bamboo forest (with tillage, fertilizer) released about the double amount of  $\text{N}_2\text{O}$  ( $15.8 \text{ kg N}_2\text{O ha}^{-1} \text{ year}^{-1}$ ).<sup>54</sup>

Besides management type, the age of pastures and forests can make a difference in  $\text{N}_2\text{O}$  emissions. For instance, young pastures of 1–3 years age had higher  $\text{N}_2\text{O}$  emissions than the original forest ( $3.1\text{--}5.1 \text{ kg N ha}^{-1} \text{ year}^{-1}$ ) but older pastures of 6 years or more had lower emissions ( $0.1\text{--}0.4 \text{ kg N ha}^{-1} \text{ year}^{-1}$ ).<sup>55</sup>

### Conclusions, forests

One-third of the total global  $\text{N}_2\text{O}$  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  $\text{N}_2\text{O}$  and such areas should not increase for the sake of greenhouse gas emission.

### Farming

In general,  $\text{N}_2\text{O}$  emissions from farmed soils have increased during the last decades. With China as example,  $\text{N}_2\text{O}$  emission has more than doubled, from  $0.5$  to  $1.1 \text{ Tg N year}^{-1}$  between 1980 and 2005,<sup>56</sup> and probably has increased since these last assessments.

$\text{N}_2\text{O}$  emissions from arable soils in temperate Europe<sup>57</sup> are very similar to arable soils in China<sup>58,59</sup> and in Canada<sup>60</sup> between  $2$  and  $5 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ , unusually above this.<sup>57</sup> For sub-boreal European arable soils, however,  $\text{N}_2\text{O}$  emissions vary in a much wider range between  $0$  and  $27 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$  due to the very high moisture in these areas.<sup>57</sup>

In the tropics, farmland  $\text{N}_2\text{O}$  emissions were estimated in three African countries to  $0.6\text{--}0.8 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ ; in six Asian countries to  $0.2\text{--}11.2 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ ; in all of Australia  $1.3$  and in three American countries  $1.4\text{--}3.8 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ .<sup>61</sup> Very high  $\text{N}_2\text{O}$  emissions around  $20 \text{ kg N ha}^{-1} \text{ year}^{-1}$  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  $0.6\text{--}2.7 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$  and forests  $0.4\text{--}0.8 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ , similar to agroforestry ( $0.1\text{--}1.1 \text{ kg N}_2\text{O-N ha}^{-1} \text{ year}^{-1}$ ). Hence, the introduction of crops in forestry may markedly reduce  $\text{N}_2\text{O}$  emissions compared to ordinary farming.<sup>62</sup>

Changing forested peatlands into farming in the Nordic countries increased N<sub>2</sub>O emissions from 2.0 to 9.9 kg N ha<sup>-1</sup> year<sup>-1</sup>.<sup>45</sup> For mineral soil, N<sub>2</sub>O emissions are normally lower than for organic soils when converting forests to farmland, estimated to be 0.25 to 2.2 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup>.<sup>45</sup>

### Crops

Not just soil characteristics, but also the type of crop that is grown can lead to large differences in N<sub>2</sub>O 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 N<sub>2</sub>O-N ha<sup>-1</sup> season<sup>-1</sup>.<sup>63</sup>

Some crops increase N<sub>2</sub>O emissions above the 2–5 kg N ha<sup>-1</sup> year<sup>-1</sup> mentioned above. One example is tea, reported to give 5.4 kg N ha<sup>-1</sup> year<sup>-1</sup><sup>64</sup> or 24.3 kg N ha<sup>-1</sup> year<sup>-1</sup>.<sup>65</sup> Another example is palm oil showing N<sub>2</sub>O emissions of up to 18 kg N ha<sup>-1</sup> year<sup>-1</sup>.<sup>66</sup> This is reflected in extremely high average N<sub>2</sub>O emissions in e.g., a country like Malaysia of 11.3 kg N ha<sup>-1</sup> year<sup>-1</sup> from farmland<sup>61</sup> because this country grows a lot of palm oil trees. Another reason for high N<sub>2</sub>O emissions is crops harvested before maturity that leave large amounts of mineral N in the soil potentially being a source of N<sub>2</sub>O.<sup>67</sup> Vegetable production in greenhouses often gets excessive amounts of N fertilizer, above 1500 kg N ha<sup>-1</sup> year<sup>-1</sup>, resulting in annual mean soil N<sub>2</sub>O emission of around 12.0 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup>.<sup>68</sup> Chinese orchards naturally release 1.96 kg N<sub>2</sub>O ha<sup>-1</sup> year<sup>-1</sup>, but when adding 300 kg N from fertilizer, N<sub>2</sub>O release increases to 4.5<sup>69</sup> and 6.2<sup>70</sup> kg N ha<sup>-1</sup> year<sup>-1</sup>. Particularly tropical orchards release much N<sub>2</sub>O. Fruit orchards go from slightly negative N<sub>2</sub>O emissions to release of 26 kg N ha<sup>-1</sup> season<sup>-1</sup> or year<sup>-1</sup>. However, greenhouse gas (GHG) emission was reduced by 28%–35% by combined applications of organic and synthetic N sources, relative to synthetic N alone.<sup>71</sup>

### 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 CO<sub>2</sub> in the atmosphere. However, in most cases, cover crops enhance N<sub>2</sub>O emissions<sup>72,73</sup> and tillage interacts with crop residues in their effects on N<sub>2</sub>O emissions. In direct drilled and reduced tillage soils crop residues give a 39% and 9% reduction in N<sub>2</sub>O emission, whereas for conventional tillage, N<sub>2</sub>O emission increased by 35% with crop residues.<sup>74</sup> Returning crop residues, N<sub>2</sub>O release was reduced by 27%<sup>75</sup> or unaffected<sup>76</sup> for paddy soils, whereas N<sub>2</sub>O emission was enhanced by 17%<sup>76</sup> or 24%<sup>75</sup> for upland soils. Similar to this, straw return reduced N<sub>2</sub>O 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 N<sub>2</sub>O formation.<sup>77</sup>

However, about 10% of the positive effect of carbon sequestration on the CO<sub>2</sub> budget of the atmosphere was eliminated by an increase in N<sub>2</sub>O emission in European grasslands.<sup>78</sup>

In arable crop rotations with clover-grass and cover crops, N<sub>2</sub>O emission was 2.9 kg N ha<sup>-1</sup> year<sup>-1</sup>. Removing clover-grass, cover crops and crop residues, and returning it the following spring after digestion gives 1.8 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup> or a 38% reduction because crop N uptake is efficient during spring as opposed to late autumn/winter.<sup>79</sup> However, postharvest N<sub>2</sub>O emissions from crop residues was the same for legumes as for non-legumes.<sup>80</sup> 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 N<sub>2</sub>O.<sup>13</sup>

### 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 N<sub>2</sub>O emissions of up to 24.2 ± 5.1 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup> in 14 studies from Europe and New Zealand.<sup>81</sup> In the same way summer drainage of rice paddies in China increased N<sub>2</sub>O emissions from 1.0 to 2.5 kg N ha<sup>-1</sup> year<sup>-1</sup>.<sup>82</sup> Drainage of organic soils and peatland in Finland increased N<sub>2</sub>O emissions from below 0.2 kg N ha<sup>-1</sup> year<sup>-1</sup> to 3.7 or 8.5 kg N ha<sup>-1</sup> year<sup>-1</sup> for bare soil or grassland, respectively.<sup>83</sup> Midsummer drainage of rice paddies also results in increased N<sub>2</sub>O emissions from 2.2 to 2.8 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup>.<sup>20</sup> A summary from 110 studies of lowland peatland says that drainage increased N<sub>2</sub>O emissions and naturally drier peats release more N<sub>2</sub>O than wetter ones.<sup>84</sup>

In contrast to the organic soils of high moisture and N<sub>2</sub>O fluxes mentioned above, semiarid areas of Colorado (USA), Saskatchewan (Canada), inner Mongolia (China) and Victoria (Australia) gave much lower N<sub>2</sub>O emissions of 0.19 ± 0.03; 0.06 ± 0.05; 0.34 ± 0.08; 0.32 ± 0.13 kg N ha<sup>-1</sup> year<sup>-1</sup>, respectively.<sup>85</sup>

### Tillage

In general, no tillage or low tillage increases N<sub>2</sub>O emissions compared to conventional tillage.<sup>29,86–88</sup> Soil moisture affects the dependence of N<sub>2</sub>O flux on tillage. On average the annual effect of no-till on N<sub>2</sub>O emissions with good, medium and poor aeration was a 0.06 kg N ha<sup>-1</sup> reduction, an 0.12 kg N ha<sup>-1</sup> increase, and a 2 kg N ha<sup>-1</sup> increase, respectively.<sup>89</sup> For rice paddies with normal fertilization, no till gives 7.4 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup> and conventional till gives 5.6 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup> or 33% less N<sub>2</sub>O. With no fertilizer, there is no difference between no till and conventional tillage giving 0.8 and 0.6 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup>, respectively.<sup>90</sup> For arable farming on well-drained soils a comparison of direct drilling (DD), reduced tillage (RT) and conventional tillage (CT) gives overall N<sub>2</sub>O emissions of 27 and 26% lower in DD and RT, respectively, compared to CT.<sup>91</sup> Replacing tillage with pesticides to keep down weeds resulted in a doubling of N<sub>2</sub>O emissions.<sup>2</sup> To conclude, reducing tillage often promotes N<sub>2</sub>O emissions during wet/moist periods, an effect not seen on well-drained soil.

### Effect of soil organism and grazers

$N_2O$  concentration in soil air increased by 20% in the presence of earthworms, with the endogeic type of worms having the largest effect.<sup>92</sup> The effects of earthworms on  $N_2O$  emissions can range from a 20% reduction to 13.4 times increase.<sup>93</sup> The increase in  $N_2O$  emission is probably related to conditions in the earthworm gut being wet and rich in nutrients,<sup>94</sup> whereas the decrease in  $N_2O$  emission relates to aeration of soil as a result of the worms' movements. Research into e.g., the effects of mycorrhiza on  $N_2O$  emissions is sparse. One study, however, showed that arbuscular mycorrhiza can reduce  $N_2O$  emissions up to 10 times due to efficient competition against other soil organisms for inorganic N,<sup>95</sup> which decreases the substrate for  $N_2O$  production.

Grazing in China on the Tibetan plateau increased  $N_2O$  emissions by 35 or 62% at light and intense grazing, respectively<sup>96</sup> whereas heavy grazing on a degraded soil led to a 30% reduction in  $N_2O$  emissions.<sup>97</sup> In New Zealand,  $N_2O$  fluxes were highest in dairy-grazed pastures (10–12 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>), intermediate in sheep-grazed pastures, (4–6 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>), and lowest in un-grazed pasture soils (1–2 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>).<sup>98</sup> Variation in food for grazers may affect their urine giving differences in  $N_2O$  emission: Animals fed with rape vs. fed with ryegrass/white clover released respectively 1.54% vs. 1.20% of the supplied urea-N as  $N_2O$ -N.<sup>99</sup>

### Nitrogen fertilizer

Not surprisingly, fertilizers containing nitrate lead to higher  $N_2O$  emissions than fertilizers containing urea, for example.<sup>100</sup> Controlled, slow-release urea gives about 25% less  $N_2O$  emission than ordinary urea.<sup>101,102</sup> The highest  $N_2O$  emissions from a grassland due to N-fertilization came from urine (10x increase), followed by slurry (9x increase), dung (8x increase),  $NH_4SO_4$  (6x increase)  $NH_4NO_3$  (4x increase) and finally, urea (3x increase).<sup>103</sup> Solid manure leads to lower  $N_2O$  emissions (0.99 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>) than liquid manure (2.83 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>) or mineral fertilizer (2.82 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>).<sup>104</sup>

Nitrogen fertilizer rate is the best single predictor of  $N_2O$  emissions from agricultural soils based on 75 publications representing 338 observations.<sup>105</sup> Globally across all ecosystems, N addition increased  $N_2O$  emission by 216%.<sup>106</sup> Annual addition of fertilizer of 35–557 kg N/ha gave a mean increase in emissions of  $2.02 \pm 0.28$  g  $N_2O$  ha<sup>-1</sup> day<sup>-1</sup> compared to unfertilized.<sup>107</sup>  $N_2O$  emissions increased abruptly at N input rates above plant uptake capacity.<sup>108</sup> Hence, in order to reduce  $N_2O$  emissions, fertilizer N applications should be kept within safe limits.<sup>109</sup>

For unfertilized maize and wheat  $N_2O$  emission was 0.7 kg N ha<sup>-1</sup> season<sup>-1</sup> compared to 2.1 kg N ha<sup>-1</sup> season<sup>-1</sup> for fertilized maize and wheat.<sup>110</sup> For maize, rice, and wheat,  $N_2O$  emission was 2.0–1.4–1.6 kg N ha<sup>-1</sup> season<sup>-1</sup>, but could be reduced to 1.7–1.2–1.4 kg N ha<sup>-1</sup> season<sup>-1</sup> with a 20% reduction in N application.<sup>111</sup> Maize production in China amended with 156 kg N ha<sup>-1</sup> (average),  $N_2O$  emission was 1.1–1.2 kg N ha<sup>-1</sup> season<sup>-1</sup> whereas 257 kg N ha<sup>-1</sup> (average) gave 1.9–2.1 kg N ha<sup>-1</sup> season<sup>-1</sup>.<sup>112</sup> Rice paddies receiving up to 125 kg N ha<sup>-1</sup> had no increase in  $N_2O$  emission, e.g., 0.5 kg  $N_2O$  ha<sup>-1</sup> season<sup>-1</sup>, with increased N-load up to 250 kg N ha<sup>-1</sup>  $N_2O$  emission increased to 1.5 kg  $N_2O$  ha<sup>-1</sup> season<sup>-1</sup>.<sup>113</sup> Fertilized orchards released double (3.6 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>) compared to unfertilized orchards (1.96 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>).<sup>1.69</sup>

Application of manure increased  $N_2O$  emissions<sup>114–116</sup> and may lead to very high emissions of up to 15 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>.<sup>117</sup> Anoxic digestion of manure may also increase  $N_2O$  emission compared to original manure following field application due to the increase in soil nitrate.<sup>118</sup> There is a discrepancy among studies whether manure increases  $N_2O$  emissions more than synthetic fertilizer<sup>114,119</sup> or if these amendments have the same effect on  $N_2O$  emissions. A positive interaction between manure and artificial fertilizer on  $N_2O$  emissions has been noted in the sense that manure amendment increases emission from fertilizer.<sup>120</sup> Different manures vary in their effect on  $N_2O$  emission with animal slurries giving a 2.2 kg N ha<sup>-1</sup> season<sup>-1</sup> increase, solid manure composts and crop residues resulting in a 1.1 kg  $N_2O$ -N ha<sup>-1</sup> season<sup>-1</sup> increase and composts mediating 0.5 kg  $N_2O$ -N ha<sup>-1</sup> season<sup>-1</sup> more than control.<sup>120</sup>

Hence, application of inorganic N often increases  $N_2O$  emissions from below 1 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup> by further 1–2 kg  $N_2O$ -N ha<sup>-1</sup> year<sup>-1</sup>. Application of wet organic fertilizer like slurry may increase emissions even further.

### Inhibitors and stimulators of $N_2O$ emissions

Several reviews describe how nitrification inhibitors reduce  $N_2O$  emissions from farmed soils. Among these, 2-chloro-6-(trichloromethyl) pyridine (nitrapyrin), dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) are the most commonly used. Reductions of about 1/3<sup>121–123</sup> or up to 1/2<sup>124–126</sup> 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.<sup>127</sup> Urease inhibitors have been reported to either decrease  $N_2O$  emissions<sup>128</sup> or have no effect on  $N_2O$  emissions,<sup>122</sup> and this discrepancy may be related to soil pH.<sup>129</sup>

Several reviews describe how biochar application reduce  $N_2O$  emissions in farmland,<sup>130,131</sup> and in greenhouses<sup>132</sup> but the effect seems to be rather short-lasting<sup>133</sup> and inconsistent.<sup>134</sup>

### Conclusions, farming

Global farm  $N_2O$  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  $N_2O$  production, drained organic wetlands should not be farmed, and semiarid farming loses less N as  $N_2O$  than the aforementioned areas with a similar yield for the same cereal crops.

Some crops release much  $N_2O$  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 N<sub>2</sub>O release per area is extremely variable across the globe, ranging from less than 0.1 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup> from oceans to 8 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup> for riparian areas. However, given the large global cover of oceans—almost 70%—, oceans contribute 20% to the global N<sub>2</sub>O 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 N<sub>2</sub>O emissions.

Even though farmland is responsible for only just above 20% of the biological N<sub>2</sub>O emissions from our globe, this is the part we can manage and should focus on if we want to reduce N<sub>2</sub>O emissions. In contrast, almost half of the global N<sub>2</sub>O 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 N<sub>2</sub>O since the middle of the 19th century.<sup>135</sup> The non-biological N<sub>2</sub>O emissions from fossil fuels are just below one-fifth of the global emissions and were not the topic of this review. To reduce N<sub>2</sub>O 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 N<sub>2</sub>O emissions from farmed land giving a 10% reduction in N<sub>2</sub>O 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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