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Nitrous oxide (N_2O) emissions from soils in warm climates

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Abstract

N_2O emission rates seem to be higher from soils in warm climates than from soils in temperate climates. Warm and moist conditions promote microbial processes that generate N_2O. Clearance of tropical forests enhances N_2O formation, but emission measurements from other agricultural operations in the tropics are few. Limiting fertilizer application to recommended rates applied at appropriate times and avoiding fallow land wherever practical serves to limit N_2O emissions. More specific advice for agriculture in warm climates requires further studies.

Background

N_2O is a natural constituent of the atmosphere, but the concentration is increasing by about 0.25% year^{-1} [17]. The preindustrial atmospheric N_2O concentration was probably about 280 ppbv, and the present concentration is 310 ppbv. This may increase to about 340 ppbv in 50 years' time if present emission rates continue unabated.

N_2O has an atmospheric lifetime of about 130 years. The natural emission rate of about 9.5 Tg N_2O-N year^{-1} (1 Tg = 10^{12} g = 1 million tonnes) has increased to about 14 Tg N_2O-N year^{-1}. Thus the increase is about 4.5 Tg N_2O-N year^{-1}, or about 50% of the natural background emission [21].

Increasing atmospheric concentration of N_2O is a matter of environmental concern:

- N_2O is a "greenhouse" gas, and present emissions contribute to about 5% of the anthropogenic greenhouse effect;
- N_2O in the atmosphere decomposes slowly in the stratosphere, partly to NO. This NO formation may contribute to a thinning of the ozone layer.

Microbiological processes are the principal source of atmospheric N_2O, both natural and anthropogenic. Transport and industrial processes also generate some N_2O, but man's major impact on the emission rate seems to be indirect: through use and management of soil and water.

Daily emission rates from soil can vary greatly, and annual emissions are difficult to quantify. However, cultivated soils seem to have an enhanced flux of N_2O compared to forest soils. Fertilizer N inputs explain some, but not all of this enhanced emission rate. Other factors including management practices also influence the emission. Bouwman [2] listed estimated fluxes from various land use regimes:

- uncultivated lands and natural ecosystems in temperate regions, mostly below 1 kg N_2O-N ha^{-1} year^{-1};
- natural ecosystems in tropical regions, mostly below 2 kg N_2O-N ha^{-1} year^{-1};
- cultivated land in temperate regions: fluxes vary greatly, but the median of 36 sets of measurements was about 2.5-3.0 kg N_2O-N ha^{-1} year^{-1}.

This paper will give a brief overview of the mechanisms and processes that determine N_2O emissions from soil, with a special emphasis on situations typical for warm climates. More details, notably on emissions in temperate climates are found in our recent review [14].

Production of N_2O in soil

N_2O emission rate from soil depends on complex interactions betwen soil, climatic and management factors that influence microbial processes. All N_2O derived from microbial processes originates either with:

- nitrification; stepwise oxidation of NH_4^+ to NO_3^-. This process requires the presence of oxygen, it is an aerobic process;
- denitrification; stepwise reduction of NO_3^- to N_2. This process requires that oxygen is in short supply, it is an anaerobic process.

N_2O is an intermediate or a byproduct in these microbial processes.

There are more published field studies on N_2O formation in soils under temperate than under warm climatic conditions, notably from agricultural soils. However, since the processes that generate N_2O are the same, deductions can also be made for tropical regions, though the controlling factors may differ markedly.

Soil is a heterogeneous material, different processes proceed at the same time, and the limiting factor for N_2O production can change, sometimes rapidly, e.g. during rain.

N_2O emission rates from soil depend on:

- the rates of nitrification and denitrification;
- the ratio of N_2O to the other, often main, reaction products, NO_3^- and N_2;
- the ease of diffusion and escape of N_2O from soil to atmosphere.

The main controllers for N_2O production and emission are:

- N availability, or more correctly soil content of NH_4^+ and NO_3^-, the substrates for N_2O producing processes;
- soil content of degradable organic carbon, which serves as energy for most microbial processes;
- soil aeration, which is determined by soil content of air and water and by soil texture.

In addition to these primary controllers, soil temperature and pH are important factors.

Some of the principal factors that influence N_2O emissions are outside the farmers control: soil type, rainfall, season and temperature. Nevertheless, some can be influenced, at least partially. Such factors are:

- soil aeration, affected by tillage;
- water status, controlled by irrigation and drainage;
- time, type, amounts and application method of fertilizers and manure;
- soil pH;
- supply of easily degradable organic material;
- cropping patterns.

Factors affecting N_2O production in soil

The potential of a soil for N_2O emission depends on the amount of N available for microbial transformation and on the rate of these processes (the turnover rate) [24]. Further, NO_3^- is both a substrate for denitrification and also an inhibitor for microbial transformation of N_2O to N_2. Hence, application of mineral fertilizers or manures is usually followed by a rapid increase in N_2O emission rates that lasts for one or a few weeks [6, 29]. Timing and magnitude of this emission depends on other soil and climatic factors.

In temperate climates the direct contribution of fertilizer application to N_2O emissions is given by the N_2O yield:

$$N_2O\ yield = \frac{N_2O\text{–}N_{(f)} - N_2O\text{–}N_{(c)}}{N\ application} \times 100\%$$

where: $N_2O\text{–}N_{(f)}$: emission from fertilized field;
$N_2O\text{–}N_{(c)}$: emission from unfertilized field.

Published N_2O yields vary within wide limits. A regression analysis of published data by Bouwman [2] point to 0.5% as the typical N_2O yield. However, this does not take into account indirect effects of fertilization practices on a soil's ability to form N_2O in the longer term e.g. enhanced fertility. Hence, Mosier [25] suggested that 1% is an appropriate factor for calculation of emission budgets. However, these numbers are derived mainly from measurements in the US, Canada and north-western Europe. In tropical and subtropical climates N efficiency (in crop production) tends to be low, below 60%, as discussed by others in this volume [1, 27, 36]. Hence, more measurements are required before such calculation factors can be used with confidence for fertilized land in warm climates.

The emission depends on the availability of O_2 for microbial processes, and the ease of escape of N_2O by diffusion through soil pores. Soil water content is a controlling factor for both. N_2O emissions are especially favoured when the soil is sufficiently wet to restrict oxygen availability. Such conditions give a high N_2O/NO_3^- product ratio in nitrification, and are also necessary for denitrification. If the soil becomes very wet, nitrification ceases, denitrification proceeds increasingly to N_2 and gas escape from the soil is hindered. Thus, a soil water content where both denitrification and nitrification can proceed, will generally give the maximum emission of N_2O. The range of this soil water content is normally in the range of 45 to 75%

water-filled pore space [9], which is normally close to the soil's field capacity, except for heavy, clay soils.

A strong increase in N_2O emission following irrigation or rainfall is normally observed. In this regard Davidson *et al.* [10] studied emissions in a dry tropical forest. Emissions were higher in the rainy season than in the dry season, and addition of water to dry soil caused rapid formation of NH_4^+ from mineralization and large pulses of N_2O emissions. Further, N_2O emissions are notably high when the soil alternates between dry and wet conditions rather than being constantly wet. This can be due to:

- increased availability of nutrients and stimulation of the microbial activity;
- rapid change of aeration status that furthers N_2O production;
- accumulation of NO_3^-, NO_2^- and dead, degradable organic materials during dry spells.

The effect of water and N inputs depends on soil texture, and vice versa. Clay soils can keep more water for longer periods than can light easily drained sandy soils. Nitrification is usually more rapid in light than in heavy soils, while denitrification is favoured in the latter. N_2O produced at depth can be reduced to N_2 as it moves upwards through the soil profile, especially when diffusion is slow as in heavy textured soils and/or if the soil is very wet. However, N_2O can escape more easily from coarse-textured soil types. Overall, clay soils seem to emit more N_2O than sandy soils, but this tendency can be masked or reversed by other factors.

Ploughing and cultivation increase aeration and ease moisture evaporation. Accessibility of crop residues for soil microbes is enhanced, and this may induce pulses of N_2O emission. However, the general impression is that the rates of denitrification and N_2O losses are lower from ploughed soils than from cultivation without tillage. Further, soil compaction caused by tractor traffic or trampling of cattle alter soil structure and generally enhance both denitrification and N_2O emission rates [12, 15].

The presence of degradable organic matter is necessary for a high level of microbial activity. Pockets of organic matter in an otherwise aerobic soil can cause conditions of local oxygen deficiency. Availability of organic matter can be an important limiting factor for N_2O emissions. N_2O emissions tend to be substantial where organic matter is available in abundance, e.g. from organic soils [11]. The effect depends on N supply. If NO_3^- is sparsely available, denitrification goes mostly to N_2, but if the NO_3^- supply is ample, reduction of N_2O is impeded and N_2O emissions can be at a high level (e.g. after fertilization). Thus, input of degradable organic materials with manure and crop residues can create conditions favourable for N_2O formation, especially when the C/N ratio in the amendment is low [4] or if it is applied together with mineral N fertilizer [6].

Microbial activity, denitrification and nitrification rates all increase with temperature. The optimum temperature for denitrification is reported to range from 30 to 67 °C. The optimum temperature range for nitrification in soils is usually between 25 and 35 °C, but both nitrifiers and denitrifiers have temperature optima adapted to their climatic regions. Laboratory studies and field measurements show that N_2O production and emission also increase with increasing temperature, at least up to 20-40 °C [6, 7, 13, 26].

Large spatial and temporal variation in N_2O emission is a problem for obtaining reliable estimates from various soils and ecosystems. Diurnal, daily and seasonal variations in N_2O emission in a field can at least partly be explained by variations in temperature [31].

The effect of soil pH on N_2O emission is complex and dependent on nutrient status. Where denitrification is the main source, increasing pH tends to decrease emissions, at least below pH 6 [35]. Where N_2O mainly originates with nitrification, emissions tend to increase as pH increases, at least in the range of pH 6 to 8 [4].

Tropical situations

Several recent publications have pointed to the tropical regions, especially the rain forests, as a dominant source of atmospheric N_2O [3, 34]. Measurements from various natural ecosystems show that emission rates from tropical soils are higher, and sometimes much higher per hectare, than their temperate counterparts [18]. Activity of man enhances these emissions through forest clearing, biomass burning and agricultural/pastoral exploitation.

The principal characteristics that tropical soils–with the exception of high mountain areas–have in common, is high temperature, and limited seasonal temperature variations. There are no special tropical soil processes that produce N_2O. It is warm and frequently moist conditions favouring rapid decomposition of organic matter [28], often with a low C/N ratio, that make the warm regions the principal background sources of N_2O [3].

Emissions from dry areas in the tropics are reported to be low during the dry season, but during the wet season and after irrigation, they can be comparable to those from areas with humid climates [12, 16, 33]. Seasonal frequent and heavy rainfall with intermittent periods of drying of the topsoil increase emissions. While there are a number of studies available for N_2O emissions from tropical forests and grasslands, there is limited data on emissions from fertilized and irrigated fields (excepting the special case of paddy rice). This is unfortunate as there may be an optimum combination of fertilizer application and irrigation practice. Currently, much effort is placed on increasing food production in the developing countries through more extensive use of irrigation. The very large expansion of irrigated cereal production in these parts of the world points to the importance of achieving more emission data from irrigated and fertilized soils in tropical regions.

In the humid tropics, soils are often acidic with pH below 6. Low pH may, to some extent, explain the high emission rates reported from these soils, at least where denitrification can be substantial, as in wet clay soils. Soils in the drier regions have higher pH values with possibilities of NO_2^- accumulation during the dry season. This NO_2^- originates with nitrification and may give high pulses of N_2O in wet periods, at least when the supply of NH_4^+ is adequate [10].

Conversion of tropical forests to pasture and other agricultural land is a major environmental issue [8]. Large amounts of N can be mobilized by such land clearance. This can enhance annual N_2O emission rates, at least as long as decomposable organic matter is present and N is available for transformation, possibly for a decade or two [19, 32, 34]. Thereafter, fluxes from cleared pastures and savannas can be lower than from similar forest sites [20, 30]. The enhanced N_2O emissions following forest clearing and pasture management are more pronounced during wet, rather than dry periods [12, 22]. Fertilization and other management practices (e.g. cultivation of forage legumes) may have potential for extending the period of enhanced N_2O emissions, but this topic has not been investigated for tropical pastures. Pastures merit further investigation as an N_2O source, as productive pastures combine good availability for microbial transformation of N and organic matter, urine patches are known to have high rates of N_2O emissions, and soil compaction by trampling of cattle can also increase N_2O emissions.

Various studies have been made where N_2O emissions from different crops have been compared. No systematic differences are apparent, with a few exceptions. Legumes contribute an N input to soils through biological N fixation. This input like other N inputs increases N_2O formation. Intercropping with legumes is practised and promoted in tropical and subtropical regions where the supply of fertilizers can be difficult.

Some important tropical crops such as banana and sugar cane may merit priority for studies. These crops are heavy fertilized. After harvest of bananas the mass of leaves are cut and left on the surface to decompose under warm, moist conditions. However, there are no reports on measurements of N_2O emissions in banana plantations. On the other hand, sugar cane residues generally decompose under more dry conditions where N_2O production should not be favoured to the same extent. A few published measurements of N_2O emissions from this crop indicate that the fluxes are not remarkable [11, 37].

Another crop more typical for warm than for temperate climates where data are available, is paddy rice. The emission rate is known to be modest while fields are flooded, but Byrnes [5] found that emissions could be as high as 6 to 7 kg N_2O-N ha^{-1} for a growing season. The N_2O originates with NO_3^- accumulated in the soil during the dry season fallow, and denitrified when the rainy season starts. However, it is not known how representative these results are for rice cultivation in general.

Some countries in temperate climates have established codes for good agricultural practice (e.g. [23]). One purpose of such codes is to prevent NO_3^- leaching, e.g. through limiting irrigation and fertilizer application to the amounts necessary to ensure optimal plant growth. Further, NO_3^- accumulation in soil should be prevented by avoiding fallow and keeping the soil under green cover for as much of the year as is practical. These measures should also serve to reduce N_2O emissions. Thus, much advice to farmers in temperate climates on how to minimize N_2O losses from agricultural land is already found in existing codes. This advice may provide a starting point for elaboration of similar information for other regions, provided care is taken to adjust the advice to local farming conditions. Agriculture in the tropics is even more diversified and complex than in temperate regions. There is ample scope for scientific work in the warm climates on increasing plant nutrient efficiency and minimizing environmental impacts of agriculture.

References

1. Agrawal RP (1995) Soil management options for improving nitrogen use. This volume
2. Bouwman AF (1990) Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In: Bouwman AF (ed) Soils and the Greenhouse Effect, pp 61–127. Chichester: John Wiley and Sons Ltd
3. Bouwman AF, Fung I, Matthews E and John J (1993) Global analysis of the potential for N_2O production in natural soils. Global Biogeochem Cycles 7: 557–597
4. Bremner JM and Blackmer AM (1981) Terresterial nitrification as a source of atmospheric nitrous oxide. In: Delwiche CC (ed) Denitrification, Nitrification and Atmospheric N_2O, pp 151-170. Chichester: John Wiley and Sons
5. Byrnes BH, Holt LS and Austin ER (1993) The emission of nitrous oxide upon wetting a rice soil following a dry season fallow. J Geophys Res 98: 22,925–22,929
6. Cates RL and Keeney DR (1987) Nitrous oxide production throughout the year from fertilized and manured maize fields. J Environ Qual 16 443–447
7. Conrad R, Seiler W and Bunse G (1983) Factors influencing the loss of fertilizer nitrogen into the atmosphere as nitrous oxide. J Geophys Res 88: 6,709–6,718
8. Cook AG, Janetos AC and Hinds WT (1990) Global effects of tropical deforestation: Towards an integrated perspective. Environ Conserv 17: 201-212
9. Davidson EA (1991) Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Rogers JE and Whitman WB (eds) Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides and Halomethanes, pp 219–235. Washington, DC: American Society for Microbiology
10. Davidson EA, Matson PA, Vitousek PM, Rile R, Dunkin K, García-Méndez G and Maass JM (1993) Processes regulating soil emissions of NO and N_2O in a seasonally dry tropical forest. Ecology 74: 30–139
11. Duxbury JM, Bouldin DR, Terry RE and Tate RL (1982) Emissions of nitrous oxide from soils. Nature 298: 462–464
12. García-Méndez G, Maass JM, Matson PA and Vitousek PM (1991) Nitrogen transformations and nitrous oxide flux in a tropical decidious forest in Mexico. Oecologia 88: 362–366
13. Goodroad LL and Keeney DR (1984) Nitrous oxide production in aerobic soils under varying pH, temperature and water-content. Soil Biol Biochem 16: 39–43
14. Granli T and Bøckman OC (1994) Nitrous oxide from agriculture. Norw J Agric Sci, Suppl 12: 1–127
15. Hansen S, Mæhlum JE and Bakken LR (1993) N_2O and CH_4 fluxes in soil influenced by fertilization and tractor traffic. Soil Biol Biochem 25: 621–630
16. Hao WM, Scharffe D, Crutzen PJ and Sanhueza E (1988) Production of nitrous oxide, methane, and carbon dioxide from soils in the tropical savanna during the dry season. J Atmos Chem 7: 93–105
17. Houghton JT, Callander BA and Varney SK (eds) (1992) Climate change. The supplementary report to the IPCC Scientific Assessment. Cambridge: Cambridge University Press
18. Keller M, Kaplan WA and Wofsy SC (1986) Emissions of N_2O, CH_4 and CO_2 from tropical forest soils. J Geophys Res 91: 11,791–11,802
19. Keller M, Jacob DJ, Wofsy SC and Hamss RC (1991) Effects of tropical deforestation on global and regional atmospheric chemistry. Climatic Change 19: 139–158
20. Keller M, Veldkamp E, Weitz AM and Reiners WA (1993) Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica. Nature 365: 244–246
21. Khalil MAK and Rasmussen RA (1992) The global sources of nitrous oxide. J Geophys Res 97: 14,651–14,660
22. Luizão F, Matson PA, Livingston G, Luizão R and Vitousek PM (1989) Nitrous oxide flux following tropical land clearing. Global Biogeochem Cycles 3: 281–285
23. MAFF (Ministry of Agriculture, Fisheries and Food) (1991) Code of good agricultural practice for the protection of water. London: Ministry of Agriculture, Fisheries and Food, Welsh Office, Agriculture Department
24. Matson PA and Vitousek PM (1990) Ecosystem approach to a global nitrous oxide budget. Processes that regulate gas emissions vary in predictable ways. Bioscience 40: 667–671
25. Mosier AR (1993) Nitrous oxide emissions from agricultural soils. In: van Amstel AR (ed) Proceedings of International IPCC Workshop; Mehane and nitrous oxide. Methods in National Emissions Inventories and Options for Control, pp 273–285. Amersfoort, The Netherlands, 3-5 February 1993.
26. Nõmmik H (1956) Investigations on denitrification in soil. Acta Agric Scand 6: 195–228
27. Pilbeam CJ and Warren GP (1995) Studies with ^{15}N fertilizer N recovery and N mineralization in semi-arid Kenya. This volume
28. Ross SM (1993) Organic matter in tropical soils: Current conditions, concerns and prospects for conservation. Prog Phys Geogr17: 265–305
29. Ryden JC (1981) Nitrous oxide exchange between a grassland soil and the atmosphere. Nature 292: 235–237
30. Sanhueza E, Hao WM, Scharffe D, Donoso L and Crutzen PJ (1990) Nitrous oxide and nitric oxide emissions from soils of the northern part of the Guayana Shield, Venezuela. J Geophys Res 95: 22,481–22,488
31. Slemr F, Conrad R and Seiler W (1984) Nitrous oxide emissions from fertilized and unfertilized soils in a subtropical region (Andalusia, Spain). J Atmosph Chem 1: 59–169
32. Steudler PA, Melillo JM, Bowden RD and Castro MS (1991) The effects of natural and human disturbances on soil nitrogen dynamics and trace gas fluxes in a Puerto Rican wet forest. Biotropica 23: 356–363
33. Vitousek PM, Matson PA, Volkmann C, Maass JM and García G (1989) Nitrous oxide flux from dry tropical forests. Global Biogeochem Cycles 3: 375–382
34. Vitousek PM and Matson PA (1992) Tropical forests and trace gases. Potential interactions between tropical biology and the atmospheric sciences. Biotropica 24: 233–239
35. Weier KL and Gilliam JW (1986) Effect of acidity on denitrification and nitrous-oxide evolution from atlantic coastal-plain soils. Soil Sci Soc Am J 50: 1,202–1,205
36. Wild A, Jenkinson D and Barraclough D (1995) The potential problems associated with introducing nitrogen fertilizers into tropical agriculture. This volume
37. Zachariassen J, Matson PA and Vitousek PM (1993) Annual nitrous oxide emissions from intensively managed soils in Maui, Hawaii. Bull Ecol Soc Am 784: 498