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Short Communication

Emissions of nitrous oxide from runoff-irrigated and rainfed soils in semiarid north-west Kenya

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Abstract

Nitrous oxide is an important greenhouse gas and contributes to stratospheric ozone destruction, but still little is known about emissions of this trace gas from soils in semiarid environments and how emissions are affected by irrigation. Therefore, nitrous oxide emissions from a runoff-irrigated and rainfed endosodi-calcaric Fluvisol in the semiarid northwest of Kenya were measured using the closed chamber method. Corresponding soil moisture and nitrate contents were determined. Nitrous oxide emissions were highly correlated with soil moisture ($r = 0.73$, $p < 0.001$). The wetting of dry soil by precipitation or irrigation resulted in high emission rates of up to 0.3 g N_2O–N ha^{-1} h^{-1}. Due to excess soil moisture these rates were lower on the runoff-irrigated plots than on the rainfed ones, but decreased at an lower rate with time. Cumulative emissions for a 1-month period were similar for both treatments (55–65 g N_2O–N ha^{-1}). The methods applied did not allow a distinction between different sources of N_2O, but considering low C and N contents of the soil and high emission rates at times of low soil nitrate content, nitrification seems to be the dominating process for the emissions observed. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Nitrous oxide; Runoff irrigation; Northern Kenya

1. Introduction

In semiarid environments land use is restricted by low and highly variable rainfall. Most of the annual precipitation is received during a few rainstorms. Under such conditions, irrigation with runoff water may be utilized as an inexpensive way to increase yields by reducing water stress. However, nutrient supplies, especially processes of the nitrogen cycle will be influenced due to the impact of the soil water regime on nitrification and denitrification.

Nitrous oxide is an important greenhouse gas and contributes to the destruction of the ozone layer (Bowden, 1986; Graedel and Crutzen, 1994). Considerable amounts of this trace gas are emitted from natural and cultivated soils through microbial processes, the most important being nitrification and denitrification (Bowden, 1986; Tiedje, 1988).

Soils of semiarid regions are often low in available nutrients and microbial activity when dry (Vlek et al., 1981). But after moistening, the microbial population strongly increases and rapid N-mineralization takes

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place (Sanchez, 1976). A high rate of respirative oxygen consumption can result in anaerobic microsites even at water contents far from saturation (Peterjohn, 1991) supporting denitrification if enough nitrate and organic carbon are available (Virginia et al., 1982; Myrold and Tiedje, 1985; Tiedje, 1988). Bowden (1986) assumes that the semiarid regions could substantially contribute to global emissions of gaseous N from undisturbed terrestrial ecosystems. Virginia et al. (1982) determined denitrification rates (nitrous oxide and dinitrogen) in desert soils with maximum emission rates of 0.2 g ($N_2O + N_2$)–N ha^{-1} h^{-1} immediately after wetting the soil. Information on emissions of N_2O alone could not be found for ecosystems so low in N and organic C (Parton et al., 1988). More data are available for environments being slightly richer in nutrients and water with 143 g N_2O–N ha^{-1} for a 2-month period (Moiser et al., 1981) and 104 g N_2O–N ha^{-1} a^{-1} (Parton et al., 1988) from a shortgrass steppe.

The aim of this study was to investigate if nitrous oxide emissions from a Fluvisol in an semiarid environment are of any importance and if they are affected by runoff irrigation.

2. Material and methods

2.1. Experimental site

The investigation was conducted near Kakuma, Turkana district in the semiarid north-west of Kenya. Mean annual temperature was 30°C, annual precipitation amounted to 302 mm in 1995 and was received during a few rainstorms resulting in the sealing of the soil surface and formation of runoff, that collected in small streams. This water was conducted into a basin and was allowed to infiltrate into the soil. Nitrous oxide emissions from runoff-irrigated and rainfed; plots (area = 200 m^2) on a sandy-loamy endosodicalcaric Fluvisol (FAO, 1990) were compared. The pH (H_2O) of the soil was 8.6, organic carbon and total nitrogen contents were low being 5.3 and 0.4 g kg^{-1} (0–0.1 m soil depth), respectively. The irrigated plot was flooded with 0.3 m of runoff water each time runoff was generated due to heavy rainstorm. The design of the irrigation scheme is described by Lehmann et al. (1997).

Samples were taken from locations of bare soil in a thornbush savanna for the rainfed and in alleys of a young plantation of *Acacia saligna* for the irrigated treatment, with four replicates from the irrigated and rainfed plot, respectively. Soil samples were taken and in situ nitrification measurements made at about 1 m distance from the chambers used for emission measurements. For the comparison of means a *t*-test was used.

2.2. Gas sampling and analysis

Nitrous oxide emissions were determined using closed chambers (Hutchinson and Mosier, 1981) covering a surface area of 0.08 m^2 with a volume of 20 dm^3. Gas samples from the chambers were taken with a 0.12 dm^3 syringe through a butyl stopper. Headspace vials (0.02 dm^3) were flushed and filled with the air sampled and stored until analysis. Samples were taken in the morning of each sampling date at $t = 0$, 1, 2, 3 h after placing the chambers air-tight onto installation rings that were permanently inserted into the soil surface. Gas analysis was performed using a gas chromatograph (Shimadzu 14 A) with electron capture detector (Clemens and Haas, 1997)

Sampling dates were adapted to precipitation events. First sampling took place 1 day after implementing the installation rings of the chambers. Further samples were taken immediately after rainstorms causing runoff and subsequently every 2–4 days. In the irrigated plot sampling was only possible after the water had almost completely infiltrated. Sampling was stopped when the topsoil had dried out, as it was assumed that emitted N_2O is formed in the top 5 cm of the soil (Denmead et al., 1979; Kliewer and Gilliam, 1995).

2.3. Soil analysis

On the days of emission measurement, nitrate and gravimetric water contents of the soil (0–0.05 m) were also determined in composite samples ($n = 4$) on both sites. Nitrate was extracted with 2 M KCl (Page, 1982) and analysed colometrically using a rapid flow analyser (Alpkem RFA 300). There was no data on ammonia, as the KCl used for extraction was contaminated with NH_4. Water content was determined by drying soil samples for 72 h at 105°C.

Net nitrification of the first month was measured in situ with a method using open polyethylene tubes adapted from Hook and Burke (1995), but modified by adding cores filled with a mixture of sand and anion exchange resin (Kaupenjohann and Kukowski, 1995) to the lower end of the tubes to quantify leached nitrate. Soil (0.01 m) was taken from the sites using a root auger (diameter: 8 cm). The soil was roughly mixed, filled into polyethylene tubes (length: 10 cm, diameter: 7.8 cm) and installed in the holes that the samples originated from. Subsamples of the soil were analysed for nitrate content. Previous to installation, the resin cores were fixed to the tubes, the hole was deepened and a layer of sand prepared at the bottom of the hole to allow free drainage of water from the cores. One month after the first flood the tubes were removed from the soil. Soil and resin subsamples were analysed for nitrate content as described above.

3. Results and discussion

Heavy rainstorms resulting in generation of runoff and flooding of the irrigated plots occurred on 27 April, 11 May and 7 July 1995. The measurement of N_2O emissions after the first flood could not be started until 30 April because the experimental site was not accessible earlier. On 12 May and 8 July only the rainfed treatment could be sampled since the water of the preceding flood had not yet infiltrated in the irrigated treatment.

The nitrous oxide emissions were in the range of 0.02–0.33 g N_2O–N ha^{-1} h^{-1} with a coefficient of variation of 5–100% (mean: 42%). After the wetting of dry soil by precipitation and resulting floods on 28 April and 7 July, N_2O emissions increased rapidly and decreased slowly with time again (Fig. 1). Emission rates after precipitation from the rainfed treatment (0.33 g N_2O–N ha^{-1} h^{-1}) were higher than those from the irrigated treatment (0.18 g N_2O–N ha^{-1} h^{-1}. However, they did not decrease as fast, as they exceeded those of the rainfed treatment after a few days. Emission rates after the flood on 11 May showed a more irregular temporal pattern. The response of N_2O emission on the wetting of soil can be explained by the influence wetting and drying cycles have on mineralization processes as described by Sanchez (1976) and Groffman and Tiedje (1998). During dry periods easily mineralizable matter accumulates with subsequent rapid mineralization of C and N, if sufficient water for microbial activity is available. This explains the strong influence the wetting and drying cycles have on the nitrate contents of the soil (0–0.05 m) in this experiment. Following intense rainstorms or flooding, the NO_3^- content in the soil decreased for a short time, probably due to leaching, before increasing again. The nitrate flush after wetting was more marked in the rainfed than in the irrigated

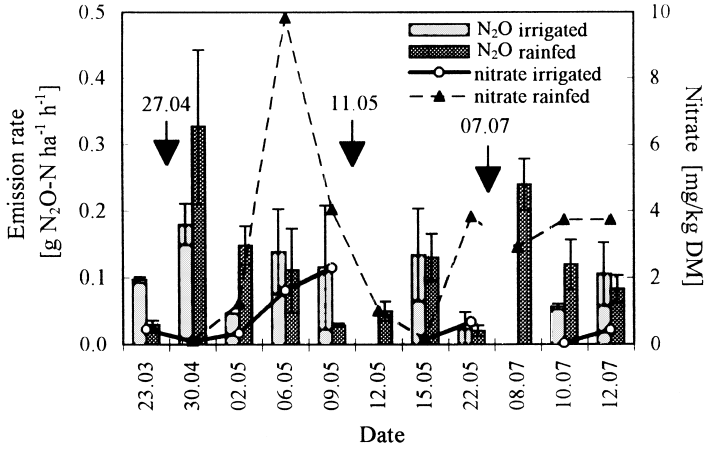

Fig. 1. Emission rates of N_2O and nitrate soil content (0–5 cm soil depth) from an irrigated and rainfed Fluvisol in semiarid north-west Kenya in 1995. Emission rates: means and standard error ($n = 4$). Nitrate: mixed sample ($n = 4$). Arrows indicate dates of floods.

treatment and was delayed by 1 week compared to the peaks of N_2O emission (Fig. 1). This suggests that nitrification is an important source of N_2O at this site. Net amounts of nitrified N (0–0.1 m) were higher in the rainfed than in the irrigated treatment amounting to 25.1 and 16.2 kg NO_3–N ha^{-1}, respectively, during a 1-month period after the first flood.

At very high water saturation, as encountered in the irrigated treatment for the first day after flooding, nitrification and thus N_2O emission originating from nitrification can be reduced by oxygen deficiency (Rosswall et al., 1990). Apart from the above explained reduction in nitrification, leaching of nitrate might also be a reason for low nitrate contents of the soil (0–0.05 m) in the irrigated treatment. Denitrification can also reduce the nitrate content of the soil, but the very low C_{org} content of the soil might be limiting for this process (Virginia et al., 1982; Myrold and Tiedje, 1985; Tiedje, 1988).

Gravimetric water content and rates of N_2O emission were correlated (Fig. 2). Up to a water content of 260 g kg^{-1}, the increase of N_2O emission with water content is significant ($p < 0.01$). This corresponds with the increase of nitrification activity described by Linn and Doran (1984). At higher water contents a significant correlation of emission rates and soil water content could not be found and emissions were reduced.

Sufficient data for calculating cumulative nitrous oxide emissions were only available for a 1-month

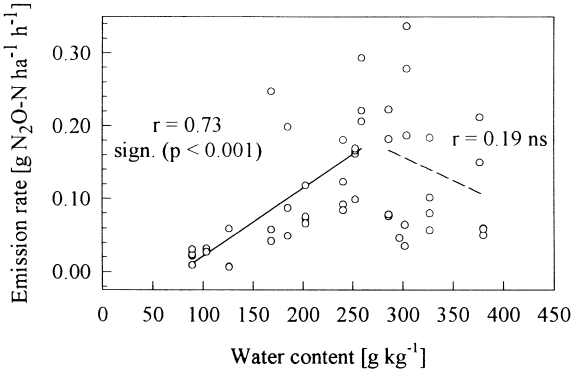

Fig. 2. Correlation of N_2O emission and gravimetric water content of the soil. Linear correlations are shown for water content <260 g kg^{-1} ($p < 0.001$) and water content >260 g kg^{-1} (not significant).

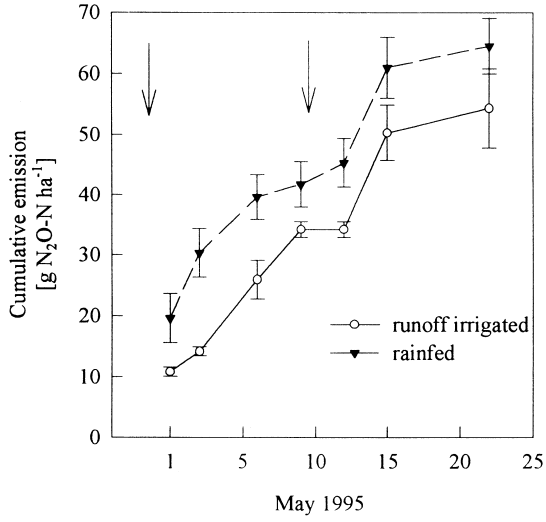

Fig. 3. Cumulative emission of N_2O from runoff-irrigated and rainfed plot. Means and standard errors ($n = 4$). Arrows indicate dates of floods.

period after the first flood and did not differ significantly ($p < 0.05$) for the two treatments. Cumulative emission from rainfed soil amounted to 64 g N_2O–N ha^{-1} being slightly higher than 54 g N_2O–N ha^{-1} from runoff-irrigated soil (Fig. 3). Runoff irrigation does not seem to increase N_2O emission from this soil.

N_2O was emitted in a relevant proportion compared to the amounts of nitrified nitrogen. About 0.26–0.34% of nitrified N was emitted as nitrous oxide (Table 1), being in the upper range of the 0.1–0.3% reported by Goodroad and Keeney (1984) from laboratory studies.

Table 1
Net nitrification (0–10 cm soil depth), nitrous oxide emission and percentage of nitrified N emitted as N_2O calculated for a 1-month period after the first flood

Treatment	Net nitrification (kg N ha^{-1})		N_2O emission (g N ha^{-1})		Percentage of nitrified N emitted (%)
	Mean	SE	Mean	SE	
Irrigated	16.2	4.3	54.3	13.0	0.34
Rainfed	25.1	5.2	64.5	8.3	0.26

Means and standard errors from four (nitrification, irrigated), three (nitrification, rainfed), and four (emission) replicates.

4. Conclusions

Although emissions of nitrous oxide are strongly dependent on the water content of the soil, no evidence for higher N_2O emissions from irrigated compared to rainfed plots could be found. Runoff irrigation only influenced the temporal pattern of emission not the overall amount. Nitrification seems to be an important N_2O producing process under these conditions and appears to be retarded by excess soil moisture.

The observed N_2O emissions were low, but considering the low C and N contents of the soil and the large area covered by semiarid lands these could be of some importance to global N_2O budgets.

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