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Emission of N_2O, N_2 and CO_2 from soil fertilized with nitrate: effect of compaction, soil moisture and rewetting

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Abstract

Soil compaction and soil moisture are important factors influencing denitrification and N_2O emission from fertilized soils. We analyzed the combined effects of these factors on the emission of N_2O, N_2 and CO_2 from undisturbed soil cores fertilized with $^{15}NO_3^-$ (150 kg N ha^{-1}) in a laboratory experiment. The soil cores were collected from differently compacted areas in a potato field, i.e. the ridges ($\rho_D = 1.03$ g cm^{-3}), the interrow area ($\rho_D = 1.24$ g cm^{-3}), and the tractor compacted interrow area ($\rho_D = 1.64$ g cm^{-3}), and adjusted to constant soil moisture levels between 40 and 98% water-filled pore space (WFPS).

High N_2O emissions were a result of denitrification and occurred at a WFPS $\geq$ 70% in all compaction treatments. N_2 production occurred only at the highest soil moisture level ($\geq$ 90% WFPS) but it was considerably smaller than the N_2O–N emission in most cases. There was no soil moisture effect on CO_2 emission from the differently compacted soils with the exception of the highest soil moisture level (98% WFPS) of the tractor-compacted soil in which soil respiration was significantly reduced. The maximum N_2O emission rates from all treatments occurred after rewetting of dry soil. This rewetting effect increased with the amount of water added. The results show the importance of increased carbon availability and associated respiratory O_2 consumption induced by soil drying and rewetting for the emissions of N_2O.

Keywords: N_2O; ^{15}N; N_2; Denitrification; Soil respiration; Soil moisture; Bulk density; N fertilizer; Rewetting

1. Introduction

Nitrous oxide (N_2O) is a climate relevant trace gas; its contribution to the anthropogenic greenhouse effect has been estimated to 6% (IPCC, 1996). Additionally, it has been shown that N_2O reacts with oxygen radicals in the stratosphere to form nitrogen monoxide, which is involved in the depletion of stratospheric ozone (Crutzen, 1981). Duxbury et al. (1993) and Isermann (1994) estimated that approximately 75% of the global, anthropogenic N_2O emissions derive from agricultural activities. The primary reason for enhanced N_2O emissions from agricultural soils are increased N inputs by mineral fertilizers, symbiotic N_2 fixation, and animal waste application. Nitrous oxide is produced in soils as an intermediate during nitrification and denitrification (Sahrawat and Keeney, 1986; Granli and Bøckman, 1994; Bremner, 1997). Labeling of mineral N pools with ^{15}N enriched nitrogen and measuring the ^{15}N abundance in the emitted N_2O was shown to be a useful tool to determine the contribution of nitrification and denitrification to N_2O emissions from soils (Stevens et al., 1997). According to a model of Davidson (1991), N_2O is primarily derived from nitrification at low and moderate soil moistures with denitrification becoming more important at soil moisture contents greater than 60% water-filled pore space (WFPS) due to a decreased O_2 supply. Soil moisture, soil respiration, soil aggregation, and soil compaction are key factors determining the aeration of soils and the formation of anoxic microsites (Granli and Bøckman, 1994), and these factors may interact and amplify each other in their effect on N_2O emission.

In experiments on potato fields, we observed a significant influence of soil compaction on N_2O fluxes. Soil compaction by tractor traffic strongly increased N_2O emissions;

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whereas soil loosening decreased N_2O fluxes (Ruser et al., 1998; Flessa et al., 2001). We ascribed these results to a change of the macro-pore volume resulting in a restricted or improved availability of O_2 in the soil. However, how soil compaction and soil moisture interact in their effect on N_2O emission remained uncertain, and the extent to which the measured emission rates were influenced by the reduction of N_2O to N_2 was not clear. Additionally, we measured high N_2O and CO_2 in situ fluxes after rewetting of dry soil in midsummer (Ruser et al., 2001). These rewetting emissions did not fit a simple linear correlation model between the gas flux rates and the percentage of water-filled pore space. To obtain more detailed information on how soil compaction, soil moisture and soil rewetting control the production and emission of N_2O, we conducted an incubation study with undisturbed, ^{15}N-fertilized soil cores taken from differently compacted areas (ridge, interrow, tractor-compacted interrow) in a potato field.

The objectives of this study were (i) to determine the effect of different bulk density and soil moisture, the latter including drying and rewetting of the undisturbed soil cores, on the emission of N_2O, N_2 and CO_2 after addition of nitrate fertilizer, and (ii) to determine the contribution of nitrification and denitrification to the N_2O emission.

2. Materials and methods

2.1. Study site

Soil cores were sampled at the Research Station of the FAM Research Network on Agroecosystems in Scheyern, approximately 40 km north of Munich in southern Germany (N 48° 30.0′, E 11° 20.7′). The experimental farm is located in a hilly landscape derived from tertiary sediments partially covered by loess. The mean annual air temperature is 7.4 °C, and the mean annual precipitation is 833 mm. Soil cores were taken from a potato plot (125 m^2) of a crop-rotation trial in October before harvest. The potatoes (*Solanum tuberosum L.*, var. Calla) were planted on May 9th, fertilized with 150 kg N ha^{-1} (ammonium urea solution) on June 10th, and harvested on October 24th. The soil type at the investigated site was a fine-loamy Dystric Eutrochrept. The topsoil had an initial pH value (10^{-2} M $CaCl_2$) of 6.1 and consisted of 23% clay, 55% silt and 22% sand. The bulk density, C_{org} and N_t contents of the three investigated areas (ridge, uncompacted interrow, tractor-compacted interrow) are shown in Table 1. Since the beginning of the FAM project in 1992, conventional farming with shallow tillage has been applied to reduce soil erosion in this undulating landscape. This practice resulted in an accumulation of organic carbon in the upper centimeters of the soil. Due to the ridge cultivation of potatoes, hilling up of this C enriched top soil, resulted in slightly higher C_{org} and N_t contents in the ridge area than in the uncompacted and the compacted interrow areas (Table 1).

2.2. Soil sampling and experimental design

One week prior to the potato harvest, undisturbed soil cores were sampled using stainless steel cylinders of 5 cm in height and an inner diameter of 8.1 cm. In total 60 soil cores were taken from each of the following areas at a soil depth of 0–5 cm: the ridge soil, the uncompacted interrow soil, and the tractor-compacted interrow soil. At the beginning of the incubation experiment, twelve soil cores from each area were used to determine soil bulk density after drying at 106 °C. Based on the mean bulk density of each sampled area we calculated the total pore space assuming a particle density of 2.65 g cm^{-3}. This information was used to adjust moisture content of the incubated soil cores to a specific water-filled pore space. The remaining 48 soil cores from each area were used for the incubation experiment. Gas fluxes (CO_2, N_2O, N_2) were measured from 16 soil cores per area (four moisture levels with $n=4$) and the remaining 32 cores were used to determine soil nitrate concentration and ^{15}N abundance in soil nitrate. The soil cores were air-dried and then they were put on glass plates and sealed at the bottom. At the end of the incubation experiment, bulk density, organic carbon concentration (C_{org}) and total nitrogen content (N_t) of all soil cores were determined ($n=48$).

During the cropping period prior to the soil core sampling, the in situ-measured soil moisture ranged between 35.1 and 70.3% water-filled pore space (WFPS) in the ridge soil and in the uncompacted interrow soil and between 70.2 and 112.2% WFPS in the tractor-compacted interrow soil. This cropping season included heavy precipitation events as well as two periods of severe

Table 1
Mean bulk density, mean C_{org} contents and mean N_t contents of the investigated soil cores from the three differently compacted areas in a potato field (48 replicates each)

Area	Bulk density		C_{org}		N_t	
	g cm^{-3}	SD	%	SD	%	SD
Ridge soil	1.02^a	(0.05)	1.63^b	(0.16)	0.187^b	(0.014)
Uncompacted interrow soil	1.24^b	(0.08)	1.43^a	(0.09)	0.173^a	(0.007)
Compacted interrow soil	1.65^c	(0.07)	1.48^a	(0.07)	0.174^a	(0.010)

Soil cores were taken from the soil depth 0–5 cm. Standard deviation (SD) is given in brackets. Statistical significant differences are indicated by different letters (Student-Newman-Keuls-Test, $\alpha<0.05$).

drought (Ruser et al., 1998). Based on these field observations, we used the following soil moisture levels in our incubation experiment: 40, 60, 70 and 90% WFPS for the soil cores from the ridge soil and uncompacted interrow soil; 60, 70, 90 and 98% WFPS for soil cores from tractor-compacted interrow soil.

The soil cores were adjusted to a specific WFPS by adding 10^{-2} M $CaCl_2$ solution. Then, the soil cores were preconditioned at 14 °C for 3 weeks. Water loss was periodically checked and readjusted to the initial soil moisture content as required. After pre-incubation, the soil cores were fertilized (day 0) by broadcast application of KNO_3 solution (39 at.% ^{15}N). Fertilizer addition was carried out by evenly applying the fertilizer solution onto the surface of the cores using a pipette. The total amount of fertilizer solution applied was 3 ml, corresponding to a maximum increase of the WFPS of 3.1%. The N application rate was 77.3 mg N per soil core or 150 kg N ha^{-1} and corresponded to good agricultural practice for the fertilization of potatoes in this region.

2.3. Automated N_2O and CO_2 flux measurements

The single cores were placed in microcosms (7 cm height, 14.4 cm inner diameter) to determine the dynamics of N_2O and CO_2 emission. A total of 12 soil cores were used per treatment: Four cores were used for the determination of trace gas fluxes, the remaining eight cores were used for the analysis of soil nitrate contents and of ^{15}N abundance in soil nitrate.

As described in detail by Hantschel et al. (1994), the microcosm cylinders were sealed gas tight at the bottom and at the top with a PVC plate. The top plates of the microcosms had two openings, one of which was used as fresh air inlet and the second was used as gas outlet and connected to a gas chromatograph equipped with a ^{63}Ni electron capture detector (ECD). N_2O and CO_2 gas fluxes were calculated using the difference of gas concentrations of the outlet air and the fresh air input taking into account the constant gas flow (20 ml min^{-1}) through the microcosm headspace. N_2O and CO_2 fluxes were measured at least three times per day and microcosm. A detailed description of the microcosm system and the configuration of the gas chromatograph was given in Flessa and Beese (1995) and in Loftfield et al. (1997). N_2O and CO_2 emission rates from the soil cores were monitored for 42 days, then the cores were dried at 30 °C for 2 weeks (day 43 to 55). On day 56 after fertilization, the cores were rewetted to the initial soil water content and N_2O and CO_2 fluxes were monitored for an additional 16 days.

2.4. ^{15}N and soil analysis

2.4.1. [^{15}N] N_2O and [^{15}N] N_2 analysis

In order to determine the N_2 emission and the N source of the emitted N_2O, we took air samples from the outlet of the microcosms by flushing exetainers (12 ml, Europe Scientific) for 2 h. The measurements of [^{15}N] N_2O and [^{15}N] N_2 were carried out for all moisture treatments and for all replicates on day 3 and day 60 and additionally on day 40 for two of the four moisture regimes (ridge soil: 40 and 60%; uncompacted interrow soil: 40 and 90%; tractor-compacted interrow soil: 60 and 98% WFPS on day 40). To obtain a higher temporal resolution of [^{15}N] N_2O emission, additional air samples were collected from single soil cores per treatment on day 1, 8, 25 and 40. The ^{15}N abundance in the N_2O and N_2 was measured using gas chromatography-isotope ratio mass spectrometry as described in detail by Schmidt et al. (1997). The ^{15}N abundance of N_2O and N_2 was determined for the outlet air and for the fresh air input. The ^{15}N abundance of the N_2O emitted was then calculated using the following mixing ratio equation:

$$^{15}N_2O \text{ emitted} = ((c_{Mix}{}^{15}N) - (c_{FA}{}^{15}N))(c_{Mix} - c_{FA})^{-1} \quad (1)$$

where $^{15}N_2O$ emitted = ^{15}N abundance of the N_2O emission [atom%]; c_{Mix} = N_2O concentration of the outlet air [ppb_{vol}], c_{FA} = N_2O concentration of the fresh air input [ppb_{vol}], $^{15}N_{Mix}$ = relative ^{15}N abundance of the N_2O in the outlet air [atom%], and $^{15}N_{FA}$ = relative ^{15}N abundance of the N_2O in the fresh air input [atom%].

The N_2 emission was calculated using the following equation:

$$\text{flux}_{N2-D} = \text{flow } 0.7808 M_W T V_m T_0 d 60 A^{-1} 10^3 \quad (2)$$

flux_{N2-D} = flux rate of N_2 from denitrification [μg N_2 m^{-2} h^{-1}], flow = air flow rate through the microcosm headspace [ml min^{-1}], 0.7808 = assumed N_2 concentration in fresh air input (decimal); MW = molar weight of N_2 (28 g mol^{-1}), T = experimental temperature (287.15 K), V_m = molar volume (22.41 l mol^{-1}), T_0 = 273.15 K, d = mixing coefficient of atmospheric N_2 with N_2 from denitrification, and A = soil core surface area [cm^2]. The mixing coefficient d was calculated from the ratios $^{30}N_2/^{28}N_2$ and $^{30}N_2/^{29}N_2$ of the samples assuming a non-random distribution of ^{15}N (Schmidt et al., 1997). Russow et al. (1996) extensively described the steps used here to calculate the mixing coefficient d.

Russow et al. (1996) quantified N_2 evolved from an ^{15}N labeled soil nitrate pool with a similar analytical equipment and determined a detection limit of 16 g N_2–N ha^{-1} d^{-1} for a static chamber system and a ^{15}N enrichment of 40 at.% in the nitrate pool. In contrast to these calculations we used a system where the headspace of the microcosms was constantly flushed with fresh air. Consequently, the detection limit in our study was about three times higher than the detection limit determined by Russow et al. (1996) and it corresponded to a N_2 emission rate of 180 μg N_2–N m^{-2} h^{-1} (43 g N_2–N ha^{-1} d^{-1}).

2.4.2. Soil and soil extracts analysis

At the end of the incubation, soil bulk density was determined from each core after drying of approximately 50 g fresh soil at 106 °C. Soil extracts were sampled on day-1, 3 and 72 by shaking 100 g fresh soil with 200 ml of 10^{-2} M $CaCl_2$ solution for 1 h. The suspension was passed through a 0.45 μm polycarbonate filter. Soil nitrate content in the solution was determined using a continuous flow analyzer (SA 20/40 Skalar Analytical, Erkelenz, Germany). Total C and N content of an aliquot of air-dried soil from day-1, 3 and 72 was determined using a CN analyzer (NA 1500, Carlo Erba). To quantify the ^{15}N abundance of the soil N, this CN analyzer was coupled to a mass spectrometer Delta E (Finnigan MAT, Bremen, Germany) for samples <1.5 at.% ^{15}N. Samples with ^{15}N enrichments >1.5 at.% were measured using an emission spectrometer (NOI-6PC, FAN, Germany), which was also coupled to a CN analyzer NA 1500.

The ^{15}N abundance in soil nitrate was determined on day-1, 3, and 72 using the diffusion method described by Jensen (1991). The ^{15}N abundance was measured by the coupling of the CN analyzer with the emission spectrometer (NOI-6PC, FAN, Germany). Due to the low NH_4^+ concentrations in the soil extracts (<15 ng N 200 ml^{-1} extract) a reliable determination of the ^{15}N abundance in soil ammonium was not possible. The ^{15}N abundance of the total soil N before nitrate addition was 0.366 at.%. We assumed the same ^{15}N abundance for the ammonium pool during the first 10 days after nitrate addition.

2.5. Calculation of the gross nitrification rate and statistics

Using the data from day 3 to day 72, we calculated the gross nitrification rate from the dilution of ^{15}N in the soil nitrate pool as described by Ledgard et al. (1998).

For the statistical comparison of the C_{org} contents, N_t contents and bulk densities (Table 1) we used the Kruskal–Wallis one-way analysis of variance on ranks followed by an all-pairwise comparison procedure (Student-Newman-Keuls-Test, $p<0.05$).

Cumulative N_2O and CO_2 emissions were calculated for the following time periods:

(i) N_2O and CO_2 fluxes after fertilization, day 0 to day 15 (15 days).
(ii) N_2O and CO_2 fluxes after rewetting, day 56 to day 71 (15 days).
(iii) N_2O and CO_2 fluxes during the whole experiment, day 0 to day 42+ day 56 to day 71 (58 days).

These cumulative fluxes of the treatments were compared using the Student-Newman Keuls test ($p<0.05$) after the Kruskal–Wallis one way analysis of variance on ranks computed significant differences between the treatments.

3. Results

3.1. Emission of N_2O, N_2 and CO_2 and nitrate contents at constant soil moisture levels

The effects of soil moisture on the emission of N_2O, N_2 and CO_2 from the ridge soil, from the interrow soil and from the tractor-compacted interrow soil are shown in Figs. 1–3 (day 0 to 40). N_2O emission rates were generally small at soil moisture levels ≤60% WFPS with mean flux rates ranging between 1 and 12 μg N_2O–N m^{-2} h^{-1}. Significantly increased N_2O emission rates were measured at soil moisture contents ≥70% WFPS, with the highest N_2O fluxes occurring at the highest soil moisture level (Figs. 1–3). The maximum N_2O flux rates were 1426 μg N_2O–N m^{-2} h^{-1} from the interrow soil (90% WFPS), 1046 μg N_2O–N m^{-2} h^{-1} from the uncompacted interrow soil (90% WFPS), and 1768 μg

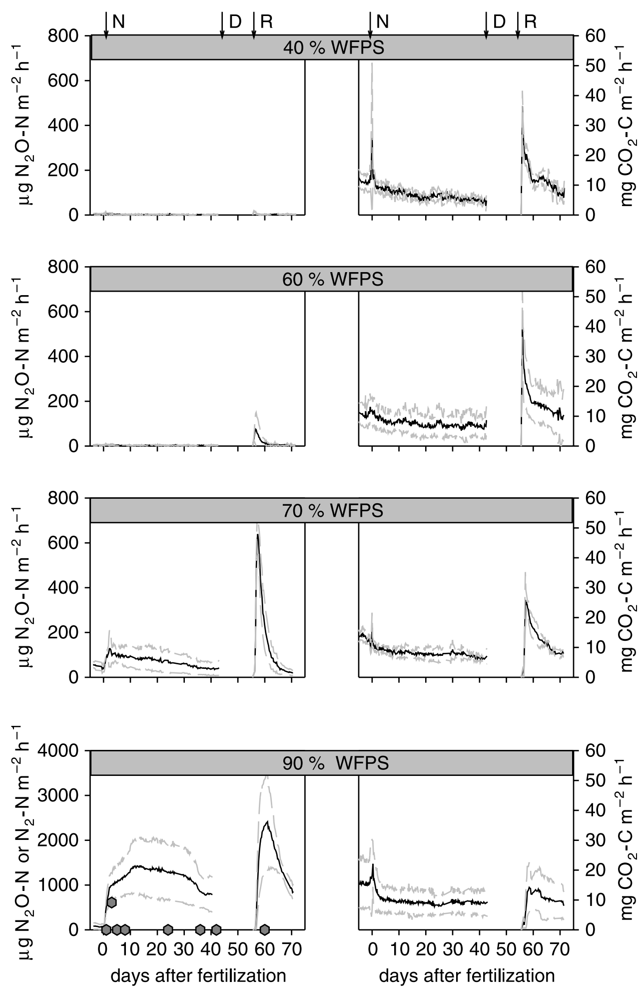

Fig. 1. Mean N_2O flux rates (solid line, $n=4$)+/− standard deviation (dotted line), N_2 flux rates (gray hexagons), and mean CO_2 flux rates (solid line, $n=4$)+/− standard deviation (dotted line) from the ridge soil (bulk density = 1.03 g cm^{-3}) at different water-filled pore space (WFPS). Nitrate addition (↓N) was carried out on day 0, the cores were removed from the system on day 42 for drying (↓D) and reinstalled and rewetted on day 56 (↓R).

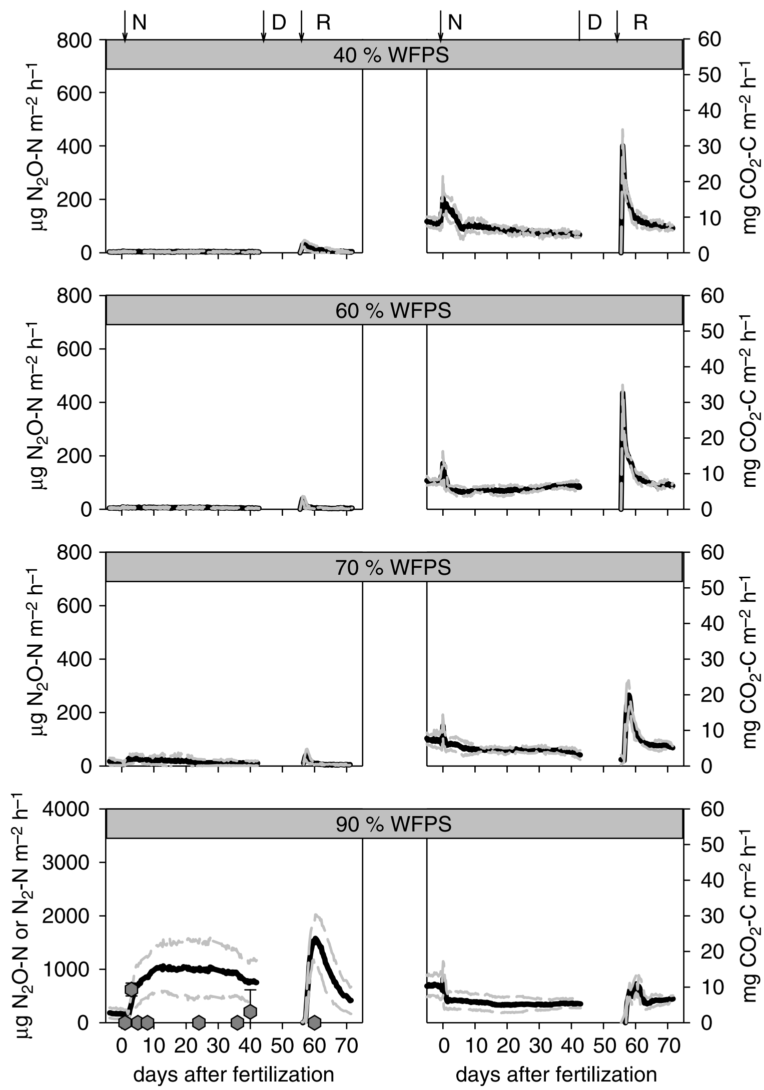

Fig. 2. Mean N_2O flux rate (solid line, $n=4$) +/− standard deviation (dotted line), N_2 flux rates (gray hexagons), and mean CO_2 flux rates (solid line, $n=4$) + /− standard deviation (dotted line) from the uncompacted interrow soil (bulk density = 1.24 g cm^{-3}) at different water-filled pore space (WFPS). Nitrate addition (↓N) was carried out on day 0, the cores were removed from the system on day 42 for drying (↓D) and reinstalled and rewetted on day 56 (↓R).

N_2O–N m^{-2} h^{-1} from the compacted interrow soil (98% WFPS).

The cumulative N_2O emission from the three areas at 90% WFPS decreased in the order ridge > uncompacted interrow > compacted interrow (Table 2) showing that the ridge soil had the highest potential of N_2O emission. Although statistically not significant, the CO_2 emission from the ridge soil was slightly higher than the CO_2 emissions from the compacted and uncompacted interrow soil (Table 3). The greater availability of organic carbon in the ridge soil became more evident when the CO_2 production rate was related to the total amount of organic C of the incubated soil cores. This specific mineralization rate increased in the order tractor-compacted interrow soil (1.6 mg CO_2–C g^{-1} SOC) < uncompacted interrow soil (3.2 mg CO_2–C g^{-1} SOC) < ridge soil (6.6 mg CO_2–C g^{-1} SOC).

N_2 losses were only observed at the highest soil moisture levels. Except for the uncompacted interrow soil, N_2 losses were highest three days after nitrate addition, they ranged between 205 and 1637 µg N_2–N m^{-2} h^{-1}. Generally, N_2 emissions were considerably smaller than the emissions of N_2O–N (Figs. 1–3). This resulted in N_2/N_2O-ratios < 0.5, where as N_2/N_2O-ratios > 1.0 were only measured two times (1.74 for the emissions from the uncompacted interrow on day 3, and 1.38 for the emissions from the compacted interrow on day 40).

Calculated over all four moisture treatments, the mean initial soil nitrate content after N fertilizer application (77.3 mg KNO_3–N per soil core) was 310, 236, and 196 µg N g^{-1} dry soil for the ridge, the uncompacted interrow, and the compacted interrow area, respectively. Taking the initial nitrate concentration of unfertilized cores into account, this corresponded to 95, 99, and 105% of the total amount of NO_3–N added.

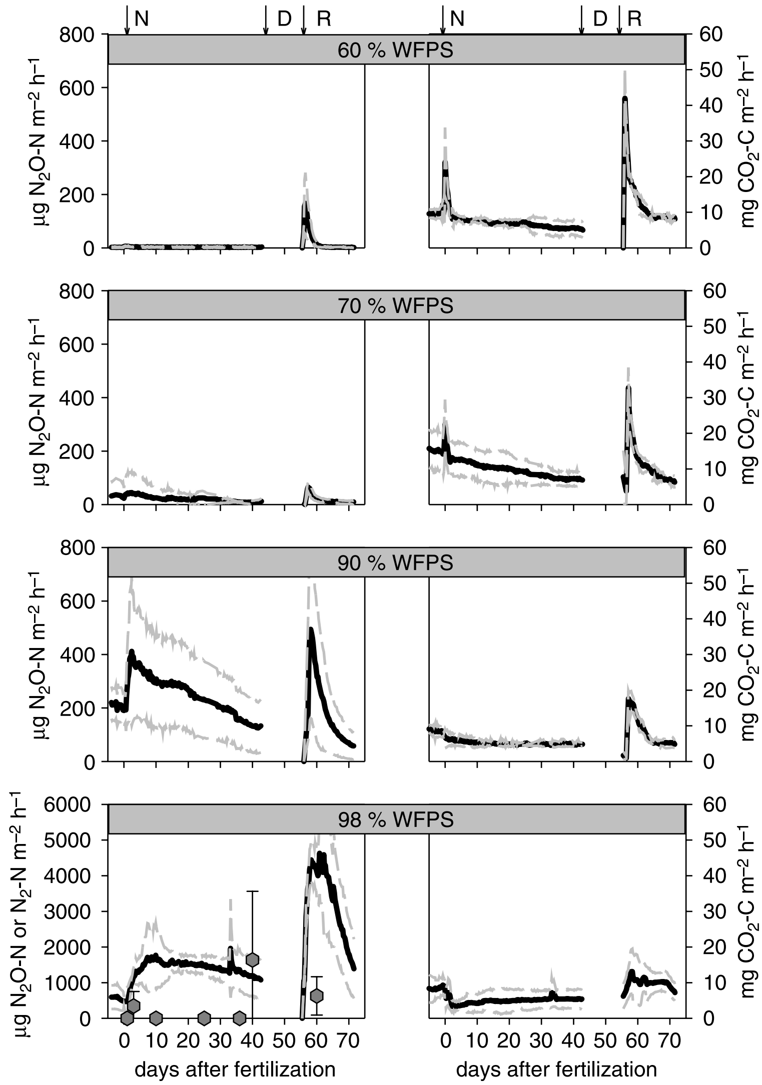

Fig. 3. Mean N_2O flux rate (solid line, $n=4$) +/− standard deviation (dotted line), N_2 flux rates (gray hexagons), and mean CO_2 flux rates (solid line, $n=4$) +/− standard deviation (dotted line) from the tractor-compacted interrow soil (bulk density = 1.64 g cm^{-3}) at different water-filled pore space (WFPS). Nitrate addition (↓N) was carried out on day 0, the cores were removed from the system on day 42 for drying (↓D) and reinstalled and rewetted on day 56 (↓R).

The CO_2 emission from the ridge soil and the uncompacted interrow soil was not influenced by the different soil moisture levels (40–90% WFPS) (Figs. 1–3, Table 3). The only statistically significant effects of soil moisture were the reduced CO_2 emission rates from the compacted interrow soil at soil moisture levels above 70% WFPS (Table 3).

3.2. Emission of N_2O, N_2 and CO_2 and nitrate contents after rewetting

Drying the soil cores for two weeks at 30 °C (day 42 until day 55) reduced N_2O fluxes to values below 1 µg N_2O–N m^{-2} h^{-1} (day 55, Figs. 1–3). Rewetting the soil cores to the initial water content on day 56 induced high N_2O emission peaks which exceeded the maximum flux rates measured after nitrate addition at constant soil water contents. The rewetting induced N_2O emission was strongly affected by the amount of water added and increased with increasing soil moisture. Maximum N_2O flux rates from the differently compacted soils were 2412 µg N_2O–N m^{-2} h^{-1} from the ridge soil (90% WFPS), 1559 µg N_2O–N m^{-2} h^{-1} from the uncompacted interrow soil (90% WFPS), and 4586 µg N_2O–N m^{-2} h^{-1} from the compacted interrow soil (98% WFPS).

Significant N_2 emission after rewetting (323 µg N_2–N m^{-2} h^{-1}) were only measured in the compacted interrow soil at the highest soil moisture level (98% WFPS). The N_2/N_2O ratio in this treatment was small (0.16) and the total gaseous N losses (N_2O–N + N_2–N) were clearly dominated by N_2O.

Calculated over all four moisture treatments, the mean soil nitrate content at the end of the experiment was 282, 203, and 177 µg N g^{-1} dry soil for the ridge,

Table 2
Cumulative N_2O–N fluxes from differently compacted soil at different soil moisture levels calculated for the three periods: After N-fertilization (15 days), after rewetting of dry soil (15 days), during the total investigated period (total, except for the two weeks of soil drying, 58 days). The total N_2O–N flux (58 days) was related to the amount of N fertilizer applied (4 replicates each)

Area	WFPS (%)	N_2O–N emission (mg N_2O–N m^{-2})			
		After N-fertilization (15 days)	After rewetting (15 days)	Total (58 days)	Related to N fertilizer (%)
Ridge	40	1^a	1^a	4^a	0.03
	60	2^a	6^b	9^b	0.06
	70	33^b	54^c	127^c	0.85
	90	412^c	553^d	1677^d	11.18
Uncompacted Interrow	40	2^a	4^a	9^a	0.06
	60	3^a	3^a	9^a	0.06
	70	8^a	4^a	20^a	0.14
	90	269^b	324^b	1218^b	8.12
Tractor-compacted Interrow	60	1^a	1^a	5^a	0.03
	70	10^a	7^b	28^b	0.19
	90	114^b	69^c	322^c	2.15
	98	493^c	1197^d	2620^d	17.46

Statistical significant differences of N_2O emission from one site during a specific period induced by soil moisture are indicated by different letters (Student-Newman-Keuls-Test, $\alpha < 0.05$).

the uncompacted interrow, and the compacted interrow area, respectively. Taking the initial nitrate concentration of unfertilized cores into account, this corresponded to 89, 85, and 95% of the total amount of NO_3–N added.

In all treatments tested, the mean cumulative CO_2 emission was greater after rewetting than at constant soil moisture after fertilizer application (Table 3). The first peak of CO_2 emission after rewetting tended to decrease with increasing soil moisture; whereas the duration of this CO_2 pulse seemed to be prolonged at higher soil moisture (Figs. 1–3).

3.3. [^{15}N] N_2O fluxes and ^{15}N enrichment of the soil nitrate

The ^{15}N abundance in the soil nitrate-N and in the N_2O–N was analyzed to calculate the contribution of nitrification and denitrification to the N_2O emitted at different levels of soil moisture. At 40 and 60% WFPS, the mean ^{15}N label of the soil nitrate-N ranged between 33.8 and 34.7 at.% ^{15}N on day 3 after fertilizer application (Fig. 4). At the end of the incubation period (day 72) the ^{15}N abundance of the soil nitrate varied between 28.2 and 29.9 at.% ^{15}N indicating a dilution of the initial nitrate pool by unlabelled soil-derived nitrate through nitrification. The gross nitrification rate was equivalent to 15.8 and 21.1% of the added N fertilizer (day 3–72, data not shown). At a WFPS $\geqq 70\%$ there was no change or only a marginal one in the ^{15}N abundance in soil nitrate during the incubation period (Fig. 4).

The ^{15}N dynamics in N_2O was significantly influenced by soil moisture. The similar ^{15}N abundance in the soil NO_3^- (on day 3) and in the N_2O emitted after N application

Table 3
Cumulative CO_2–C fluxes from differently compacted soil at different soil moisture levels calculated for the three periods: after N-fertilization (15 days), after rewetting of dry soil (15 days), during the total investigated period (total, except for the two weeks of soil drying, 58 days) (4 replicates each)

Area	WFPS (%)	CO_2 emission (g CO_2–C m^{-2})		
		After N-fertilization (15 days)	After rewetting (15 days)	Total (58 days)
Ridge	40	3.46^a	4.51^a	11.57^a
	60	3.42^a	5.22^a	13.07^a
	70	3.51^a	5.23^a	13.22^a
	90	3.43^a	4.60^a	13.77^a
Uncompacted Interrow	40	3.37^a	3.71^b	10.78^a
	60	2.23^a	3.58^b	9.61^a
	70	2.09^a	$3.05^{a,b}$	7.92^a
	90	2.42^a	2.54^a	8.29^a
Tractor-compacted Interrow	60	3.34^b	4.91^a	12.28^a
	70	4.35^b	4.70^a	14.49^a
	90	2.17^a	3.11^a	8.45^a
	98	1.76^a	3.83^a	8.96^a

Statistical significant differences of CO_2 emission from one site during a specific period induced by soil moisture are indicated by different letters (Student-Newman-Keuls-Test, $\alpha < 0.05$).

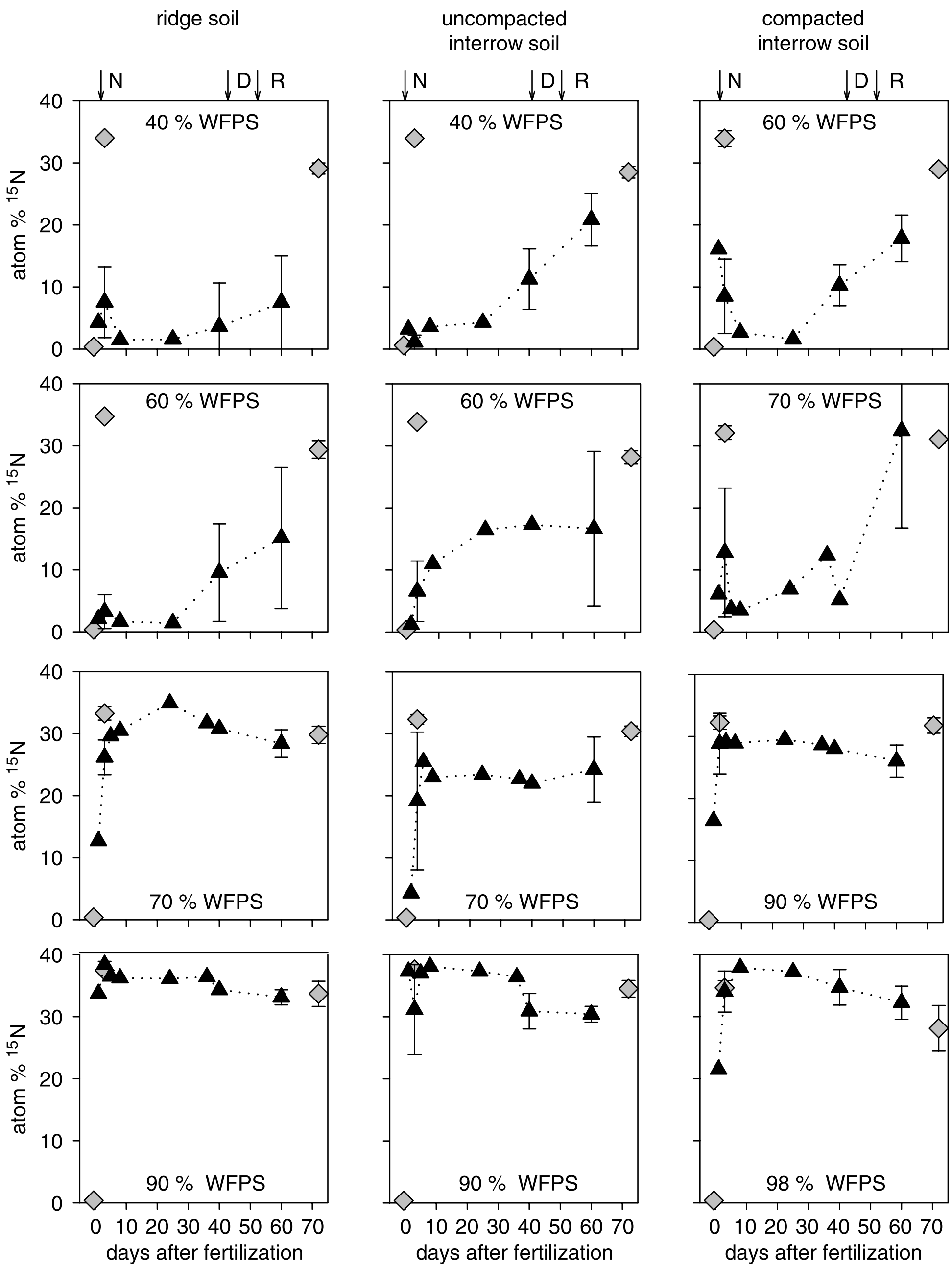

Fig. 4. Mean ^{15}N abundance in soil nitrate (gray diamonds, $n=4$, +/− standard deviation) and ^{15}N abundance in N_2O emission (dotted line; black triangles) from the ridge soil (left column), from the uncompacted interrow soil (middle column) and from the tractor-compacted interrow soil (right column) at different water-filled pore space. Nitrate addition (↓N) was carried out on day 0, the cores were removed from the system on day 42 for drying (↓D) and reinstalled and rewetted on day 56 (↓R). The $^{15}N_2O$ data include measurements with replicates ($n=4$, +/− standard deviation) and data from single soil cores (without standard deviation).

indicated that N_2O was mainly produced by denitrification at a soil moisture content ≥70% WFPS (Fig. 4). In contrast, the mean ^{15}N abundance in N_2O during the first 10 days after N application was much smaller for the soil moisture levels ≤60% WFPS. This indicates that the low N_2O emissions observed in these treatments were mainly caused by nitrification. Calculated for the first 10 days after fertilization, nitrification accounted for 83–96% of the total N_2O emission from the soil cores sampled in the ridge and the interrow area at soil moisture levels ≤60% WFPS. The corresponding value for the soil cores from the compacted interrow at 60% WFPS was 75%. There was a considerable increase in $^{15}N_2O$ with time for all soil cores with soil moisture levels ≤60% WFPS.

Related to the amount of N nitrified at a WFPS ≤60% in the ridge soil and in the uncompacted interrow soil (calculated from the dilution of ^{15}N in the nitrate pool) the N_2O–N emitted during the first 2 weeks following nitrate addition varied from 0.16 to 0.39% of the gross nitrification rate.

4. Discussion

4.1. Emissions after nitrate addition

Increasing N_2O emission rates with increasing soil water contents were often reported from laboratory and field studies and attributed to an increased denitrification activity induced by a reduced O_2 diffusion into the soil (i.e. Mosier et al., 1986; Clayton et al., 1994; Flessa et al., 1995; Corre et al., 1996; MacKenzie et al., 1997; Dobbie and Smith, 2001; Ruser et al., 2001). The strong increase in N_2O emissions between 60 and 70% WFPS supports the hypothesis of a threshold WFPS for N_2O production by denitrification as proposed by Davidson (1991). A similar WFPS threshold for strongly increased N_2O emissions from soils was also reported by De Klein and Van Logtestijn (1996) and by Dobbie and Smith (2001).

At 90% WFPS, the ridge soil had the highest N_2O emission rates. This result suggests that the N_2O emission at this WFPS was influenced by the availability of organic carbon. The greater specific substrate availability may have favored the formation of anoxic microsites, which are known to promote N_2O emissions, especially if soil nitrate availability is high (Flessa and Beese, 2000).

In a field study at the same site, Ruser et al. (1998) found that the mean water-filled pore space of the ridge soil was 49% during the cropping period and that it never exceeded 67%. Furthermore, they found significantly lower N_2O emissions from the ridge soil than from the interrow soil where the mean WFPS percentage was considerably higher (58% in the uncompacted interrow soil and 85% in the tractor-compacted interrow soil). The results from our experiment demonstrate that the low N_2O emission from the ridge soil under field conditions were mainly a result of the persistent low soil water contents.

Our data show that different soil moisture contents after N fertilization considerably influenced the fertilizer-related N_2O emission factors and that these emission factors strongly increased at a WFPS $\geq 70\%$. This may be a key factor for the great inter-annual variability of N_2O emission factors found in field studies even if soil management and fertilization was nearly unchanged (Kaiser et al., 1998; Kaiser and Ruser, 2000; Leidel et al., 2000). The importance of soil moisture in fertilizer-induced N_2O emissions was also stressed by Dobbie et al. (1999), who found a strong positive correlation between the amount of rainfall during the first 4 weeks after N application and the cumulative N_2O emission in field measurements.

In all differently compacted areas, N_2 emissions were only observed in the highest soil moisture treatment. This matches the assumption of many models, that the portion of N_2 to the total gaseous N-losses during denitrification increases with increasing soil water contents (Del Grosso et al., 2000; Parton et al., 1996; Davidson, 1992). As a result of temporally different responses of the enzymes involved in nitrate- and N_2O-reduction during denitrification the N_2/N_2O ratio is not stable over time (Firestone and Tiedje, 1979). Weier et al. (1993) investigated the N_2/N_2O-ratio produced during denitrification in four soils with different texture. Generally, the N_2/N_2O ratio was highest during the first 3 days of the incubation experiment and declined to day 5 in the treatments where no glucose as carbon source was added. This is in good agreement with our results, where the N_2 emissions and the N_2/N_2O-ratios were highest 3 days after the nitrate addition followed by a decline in the N_2 emission.

The generally low N_2 emissions even at high soil moisture levels were probably a result of the high soil nitrate content in all soil cores. High soil nitrate concentrations have been shown to inhibit N_2O reductase activity due to the competitive effect of nitrate and N_2O as terminal electron acceptors during denitrification (Cho and Sakdinan, 1978; Blackmer and Bremner, 1978). A similar effect of soil nitrate availability on the N_2/N_2O ratio was also found in several field studies (Yamulki et al., 1995; Swerts et al., 1996).

Except for the emission from the compacted interrow soil at high soil moistures, CO_2 emissions were not influenced by the different soil moisture levels. These results show that a wide range of soil moisture provided optimal conditions for heterotrophic activity in this soil. This observation agrees with the results of field studies on CO_2 emissions from grassland (Frank et al., 2002) and forest soils (Drewitt et al., 2002) which indicated only a minor or no relationship between CO_2 emissions and soil moisture contents. Doran et al. (1990) proposed quadratic models to describe the relationship between WFPS and soil respiration in differently textured soils. They found highest soil respiration rates between 40 and 70% WFPS in most of the soils they investigated. At lower WFPS, soil respiration was reduced considerably by water availability; whereas at higher WFPS CO_2 production decreased as a result of reduced aeration. Our results indicate that the relation between soil respiration and WFPS was influenced by the existence of macropores because the CO_2 emission rates from the compacted interrow soil, where macropores were largely destroyed by tractor traffic, were significantly reduced at soil moisture levels above 70% WFPS.

4.2. Emission after rewetting

Short-term N_2O pulses after rewetting dry soil have been observed in several studies (Smith and Parsons, 1985; Cates and Keeney, 1987; Rudaz et al., 1991). The magnitude of the rewetting-induced N_2O emissions, the contribution of nitrification and denitrification to the emissions, as well as the ratio of N_2/N_2O during denitrification were shown to be highly variable (Firestone and Tiedje, 1979; Firestone and

Davidson, 1989). Firestone and Tiedje (1979) found increasing amounts of N_2O from denitrification when soil moisture reached or exceeded field capacity after rewetting.

The high NO_3^- concentrations were probably the key factor resulting in N_2O being the main end product of denitrification. The results show that significant N_2 emission after rewetting was restricted to the treatment in which soil water saturation and denitrification activity was greatest.

As compared to nitrate addition, the higher CO_2 fluxes after rewetting indicate the release of easily available organic matter during drying-rewetting which resulted in an increased microbial C consumption following rewetting. The change in C availability induced by rewetting events was also shown in field and laboratory studies on the controls of dissolved organic carbon (DOC) production in soils. Rewetting after dry periods increased the concentration of DOC considerably (Kalbitz et al., 2000). As summarized by Lundquist et al. (1999), several processes may have contributed to increased DOC and C availability after drying-rewetting: (i) reduced microbial decomposition in dry periods, (ii) enhanced turnover of microbial biomass, and (iii) release of available carbon by the disruption of soil aggregates. The increased C turnover following rewetting is associated with an enhanced O_2 consumption which stimulates denitrification (Flessa and Beese, 1995). The observed phenomenon of a decreased height but prolonged duration of CO_2 emission pulses with increased soil moisture after rewetting might be a result of the reduced gas exchange.

4.3. [^{15}N] N_2O fluxes

The low gross nitrification at high soil moistures seemed to be affected by a reduced aeration because there was no change or only a marginal one in the ^{15}N abundance in soil nitrate during the incubation period.

The results on the sources of the N_2O emission as affected by soil moisture agree with the observations of Wolf and Russow (2000) and of Russow et al. (2000) who found that N_2O emission from soils originated mainly from nitrification at soil moistures below 60% WFPS. Additionally, our results show that the proportion of N_2O evolved during nitrification was rather small. Related to the amount of N nitrified at a WFPS $\leq 60\%$ in the ridge soil and in the uncompacted interrow soil (calculated from the dilution of ^{15}N in the nitrate pool) the N_2O–N emitted during the first two weeks following nitrate addition varied from 0.16 to 0.39% of the gross nitrification rate. The considerably increase in $^{15}N_2O$ 2 weeks after the nitrate addition was probably a result of an increasing ^{15}N labeling of the soil NH_4^+ pool caused by remineralization of the $^{15}NO_3^-$ added. Therefore, it was difficult to assess the contribution of nitrification and denitrification to the N_2O emission induced by rewetting from the ^{15}N data because we cannot exclude an increasing ^{15}N labeling of the soil NH_4^+ pool during our experiment. However, the prompt increase in N_2O emission by several orders of magnitude directly after rewetting is more typical for denitrification than for nitrification (Firestone and Davidson, 1989) and the high ^{15}N labeling of the N_2O produced also suggests that the increased C availability and O_2 consumption induced by rewetting favored N_2O production by denitrification.

5. Conclusions

Our results show the decisive influence of soil moisture on N_2O production by nitrification and denitrification in fertilized soil and on the related N_2O emission rates. They confirm model assumptions that N_2O emission induced by denitrification increases when soil moisture rises above 60–70% WFPS and that the N_2/N_2O ratio during denitrification is small when soil nitrate contents are high. Under our experimental conditions (high nitrate availability) N_2O was the primary end product of denitrification. Additionally, the results show that the strongly increased N_2O emissions found in field experiments from compacted soils (Hansen et al., 1993; Ruser et al., 1998) are primarily a result of an increase of the water-filled pore space. Additionally, reduced plant N uptake in compacted soils was shown to contribute to high N_2O emission rates (Ruser et al., 1998).

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