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RESEARCH ARTICLE

Emissions of N_2O from fertilized and grazed grassland on organic soil in relation to groundwater level

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Abstract Intensively managed grasslands on organic soils are a major source of nitrous oxide (N_2O) emissions. The Intergovernmental Panel on Climate Change (IPCC) therefore has set the default emission factor at 8 kg N–N_2O ha^{-1} year^{-1} for cultivation and management of organic soils. Also, the Dutch national reporting methodology for greenhouse gases uses a relatively high calculated emission factor of 4.7 kg N–N_2O ha^{-1} year^{-1}. In addition to cultivation, the IPCC methodology and the Dutch national methodology account for N_2O emissions from N inputs through fertilizer applications and animal urine and faeces deposition to estimate annual N_2O emissions from cultivated and managed organic soils. However, neither approach accounts for other soil parameters that might control N_2O emissions such as groundwater level. In this paper we report on the relations between N_2O emissions, N inputs and groundwater level dynamics for a fertilized and grazed grassland on drained peat soil. We measured N_2O emissions from fields with different target groundwater levels of 40 cm ('wet') and 55 cm ('dry') below soil surface in the years 1992, 1993, 2002, 2006 and 2007. Average emissions equalled 29.5 kg N_2O–N ha^{-1} year^{-1} and 11.6 kg N–N_2O ha^{-1} year^{-1} for the dry and wet conditions, respectively. Especially under dry conditions, measured N_2O emissions exceeded current official estimates using the IPCC methodology and the Dutch national reporting methodology. The N_2O–N emissions equalled 8.2 and 3.2% of the total N inputs through fertilizers, manure and cattle droppings for the dry and wet field, respectively and were strongly related to average groundwater level ($R^2 = 0.74$). We argue that this relation should be explored for other sites and could be used to derive accurate emission data for fertilized and grazed grasslands on organic soils.

Keywords Nitrous oxide emission · Emission factor · Tile drains · Fertilizer application

Introduction

Nitrous oxide (N_2O) is an important greenhouse gas with a global warming potential of approximately 310 molar CO_2 equivalents (Forster et al. 2007). Most N_2O originating from agricultural soils is a by- or end-product of nitrification, nitrifier denitrification or denitrification (Wrage et al. 2001). In general, denitrification is considered as the major N_2O producing process, which is favoured by humid

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conditions in soil and ample availability of organic matter (Tiedje et al. 1984). Such conditions are usually found in shallow peat soils in The Netherlands and consequently these soils are considered major contributors to the national N_2O emission (Velthof and Oenema 1995a).

All countries that have signed and ratified the Kyoto protocol on climate change have the obligation to report annual national total greenhouse gas emissions per sector. For these reports the greenhouse gas emissions can be estimated at different levels of complexity (Tiers). The most straightforward method (Tier 1) is the method provided by the IPCC (Intergovernmental Panel on Climate Change). The IPCC guidelines prescribe to estimate direct emission of N_2O from managed organic (i.e. peat) soils by (De Klein et al. 2006):

$$N_2O - N_{direct} = N_2O - N_{input} + N_2O - N_{OS} + N_2O - N_{PRP} \quad (1)$$

where $N_2O–N_{input}$ is the annual direct $N_2O–N$ emissions from N inputs to managed soils, $N_2O–N_{OS}$ is the annual direct $N_2O–N$ emissions from managed organic soils and $N_2O–N_{PRP}$ is the annual direct $N_2O–N$ emissions from urine and dung inputs from grazing cattle. Substituting Eq. 1 with the appropriate emission factors gives the Tier 1 approach for grazed grasslands on organic soils in temperate climates (De Klein et al. 2006):

$$N_2O - N_{direct} = (F_{SN} + F_{ON} + F_{SOM}) \cdot EF_1 + F_{OS,CG,TEMP} \cdot EF_{2CG,TEMP} + F_{PRP,CPP} \cdot EF_{3PRP,CPP} \quad (2)$$

where F refers to total amounts of applied or released N via synthetic fertilizer (SN; kg N year^{-1}), organic additions (ON; kg N year^{-1}), mineralization of soil organic matter as a result of changes in land use or management (SOM; kg N year^{-1}), management and drainage of organic soils (OS, CG, TEMP; ha) and urine and dung of grazing cattle (PRP, CPP; kg N year^{-1}). For soils in temperate climates without crop residues the emission factors (EF) are set at: $EF_1 = 0.01$ kg N–N_2O kg N^{-1}, $EF_{2CG,TEMP} =$ 8 kg N–N_2O ha^{-1} year^{-1}, $EF_{3PRP,CPP} = 0.02$ kg N–N_2O kg N^{-1} (IPCC 2006).

For the national reporting obligations The Netherlands use a slightly modified approach (Tier 2) to estimate the direct emission of N_2O from managed organic soils, viz. 4.7 kg N ha^{-1} year^{-1} + 1% of the N application via faecal deposition (dung) and ammonium fertilizers and 2% of all other N inputs (Protocol 8132 Direct emissions from agriculture, van der Hoek et al. 2007). However, neither approach, i.e. Tier 1 nor Tier 2, accounts for differences in groundwater level which are expected to have distinct effects.

Peat lands in the western part of The Netherlands are commonly used for dairy farming. Groundwater levels fluctuate between 0 (ponded) and approximately 1 m below soil surface and the soils are drained using ditches and tile drains. The water filled pore space (WFPS) of the soil is a main driving factor of N_2O emission from these soils (Velthof et al. 1996). Consequently drainage conditions and groundwater level positions have been recognized as potential factors for controlling N_2O losses from organic soils (Flessa et al. 1998; von Arnold et al. 2005).

To improve the workability of the fields and to decrease subsidence of the peat soils an increasing area of the western peat lands in The Netherlands is drained using tile drains below ditch water level. Such drains may decrease the amplitude of groundwater fluctuations, i.e. suppress low groundwater levels in summer by infiltration of ditch water and suppress shallow groundwater levels in winter by draining the fields (Pleijter and van den Akker 2007). Thereby tile drains may decrease the alteration of aerobic and anaerobic conditions in soil and consequently affect N_2O emissions.

In this study we examined the effect of differences in groundwater level and presence of tile drains on N_2O emissions from an intensively managed grassland on peat soil. Measurements were performed on fields with different target groundwater levels. Measurements were performed for 5 years in the period 1992–2007. In 2005, tile drains were installed at different inter drain distances to study the effect of tile drains on N_2O emissions. In this paper we combine new data on N_2O measurements (from hereon referred to as '2006–2007 experiment') with previous data on the same site so as to assess the effect of groundwater level and drain distances on N_2O emissions. We compare these emission data with the aforementioned official estimates to evaluate the official approaches.

Materials and methods

Site description

Between 1992 and 2007 measurements were performed for 5 years at experimental dairy farm 'Zegveld' located in the Western part of the Netherlands (52°26′N, 4°48′E). Two blocks, each covering several fields, had different target groundwater levels of 40 cm below soil surface, which will henceforth be called 'wet' fields and 55 cm below soil surface, which will henceforth be called 'dry' fields. The soil was classified as Terric Histosol according to FAO classification. Some site characteristics are listed in Table 1. The fields were grazed and fertilized according to common agricultural practices and received approximately 380 kg N ha^{-1} $year^{-1}$ (Table 2).

The 2006–2007 experiment

In 2005 tile drains were established at approximately 10 cm below ditch water level in each field. In summer, i.e. during the period of precipitation deficit, groundwater levels dropped below the ditch water level and the tile drains served as conduits for infiltration thereby suppressing the oxidation of peat. In winter, i.e. during the period of precipitation surplus, groundwater levels were above ditch water levels and the tile drains served drainage purposes. Tile drains included a control (no drains) and drains at 4, 8 and 12 m inter drain distance. Flux measurements were performed in duplicate in both fields at three locations: (1) above the drain, (2) at ¼ inner drain distance and (3) at ½ inter drain distance (halfway between the drains). Each measurement was replicated near the ditch (approximately 1 m from the ditch bank) and in the middle of the field to study spatial patterns related to distance to the ditch. In total 96 measurements were performed on each sampling occasion (Fig. 1).

Measurements were performed once a month (regular sampling scheme) and more intensively after three selected management activities ('events'): two manure applications and one fertilizer application. Measurements were performed at approximately 1, 7, 14, 21 and 28 days after the selected events. In total 86 sampling events were performed between October 2005 and October 2007. Nitrous oxide fluxes were measured using vented closed flux chambers (Ø = 30 cm) as described by Velthof and Oenema (1995b) and Van Groenigen et al. (2004). Fluxes were calculated from the differences between ambient N_2O concentrations and the N_2O concentrations in the flux chambers after closing for approximately 30 minutes using a photoacoustic infrared gas analyzer, assuming linear increase (which was occasionally checked). Cumulative fluxes were calculated by linear interpolation between sampling dates. At each sampling event air and soil temperatures and groundwater levels were measured using groundwater sampling tubes. From February 2007 onwards soil moisture and mineral N contents of soil samples (0–20 cm) were analyzed at 12 locations per field: three inter drain distances (control, 4 and 12), two sides of the field (ditch versus centre) and above and halfway between the drains (Fig. 1). The emission data were log transformed to obtain normal distributions. The data were treated as random samples, although variations at higher order level may be underestimated, because it was impossible to include multiple replicates of the groundwater levels and drain treatments.

Table 1 Selected site characteristics

	Wet field	Dry field
Total N (g kg^{-1})[a]	16.3	18.6
Total C (g kg^{-1})[a]	156	223
pH-KCl[a]	5.0	4.7
Clay content (g kg^{-1})[a]	284	287
Dry bulk density (0–30 cm, kg dm^{-3})[a]	0.52	0.45
Average groundwater level (cm below soil surface, average, minimum and maximum)		
1992	24.4 (1–73)	40.4 (10–88)
1993	21.3 (2–61)	35.1 (2–74)
2002	23.1 (0–39)	31.8 (3–60)
2006	23.4 (0–58)	45.4 (0–78)
2007	12.4 (0–55)	33.2 (0–65)

[a] Data taken from Velthof and Oenema (1995a) and referring to field codes 8b (wet field) and bos6 (dry field)

Previous experiments on the same site

To relate N inputs and groundwater level to annual N_2O–N emissions we combined the '2006–2007

Table 2 Nitrogen inputs and N_2O emissions per field and (experimental) year

Year	Field[a]	Average temperature (°C)[b]	Cumulative precipitation (mm $year^{-1}$)[b]	Drainage condition	Fertilizer N (CAN)	Manure	Dung and urine[c]	N_2O–N emission (kg ha^{-1} $year^{-1}$)	Total N input (kg ha^{-1} $year^{-1}$)	N_2O–N/N input
1992	Bos6	10.5	918	Dry	161	0	194	36	355	0.10
1993	Bos6	9.6	880	Dry	323	0	221	39	544	0.07
2002[d]	3	10.8	891	Dry				18	197	0.09
2006	2	11.2	765	Dry	103	70	151	32	324	0.10
2007	2	11.2	920	Dry	113	68	269	23	450	0.05
1992	8b	10.5	918	Wet	267	0	254	12	521	0.02
1993	8b	9.6	880	Wet	464	0	249	17	713	0.02
2002[d]	13	10.8	891	Wet				13	232	0.06
2006	13	11.2	765	Wet	122	44	75	10	241	0.04
2007	13	11.2	920	Wet	70	82	100	6	252	0.02

[a] The field codes refer to different fields within dry and wet blocks

[b] Average temperatures and cumulative precipitation refer to calendar years

[c] Nitrogen inputs through dung and urine were calculated after Bussink (1994) and Van Beek et al. (2003). Stocking density was adjusted in such a way that dairy cows could graze the sward for 2 days

[d] In the experiments of Jacobs et al. (2003) only total N inputs, including fertilizer, manure and dung and urine of grazing cattle, were recorded

experiment' with the datasets of Velthof et al. (1996) and Jacobs et al. (2003) from the same blocks of fields. All experiments had a comparable experimental design although the scopes of the studies differed: Velthof et al. (1996) studied seasonal variations in N_2O losses from managed grassland on peat soil, while Jacobs et al. (2003) focused on the total greenhouse gas emission, including CO_2 and CH_4. In the study of Velthof et al. (1996) the use of manure was excluded, whereas in the study of Jacobs et al. (2003) and the present study common agricultural practices were used (Table 2). By combining the three datasets we obtained N_2O flux data covering a 5 year period between 1992 and 2007 for the wet and dry fields. Different fields were used for the different experiments, but the groundwater level regimes within the 'dry' block and within the 'wet' block were similar. Some general information about the experiments is provided in Table 3. More information about the experiments prior to 2006 can be found in Velthof et al. (1996) and Jacobs et al. (2003).

To relate N_2O emissions to N inputs through animal excreta, organic and mineral fertilizers the N_2O loss fraction was calculated using Eq. 3 with all units in kg N ha^{-1} $year^{-1}$.

$$N_2O\,\text{lossfraction} = N_2O - N\,\text{emission}/\text{total N inputs} \tag{3}$$

We could not derive emission factors like in Eqs. 1 and 2, because of lack of baseline data, i.e. emission data from unfertilized fields for all years and because in the study of Jacobs et al. (2003) no distinction was made between the different sources of N inputs.

Results

The 2006–2007 experiment and the effects of tile drains

In general groundwater levels were concave in summer with lower groundwater levels in the centre of the fields compared to the ditch sides. In winter the reverse occurred and groundwater levels were convex with higher groundwater levels in the centres of the fields compared to the ditch sides. Hence, in the middle of the field more fluctuations in groundwater level occurred compared to the ditch sides. The presence of tile drains reduced the amplitude of these groundwater fluctuations, i.e. resulted in shallower

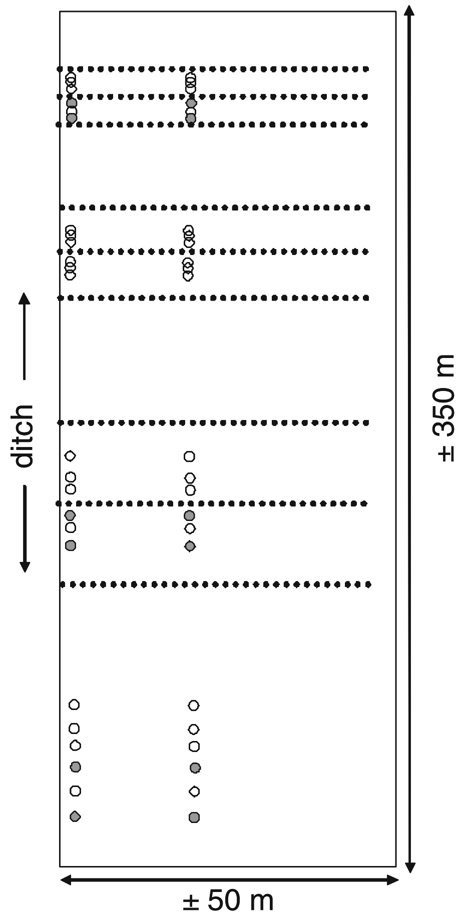

Fig. 1 Schematization of experimental design of 2006–2007 experiment. Measurements (*white and grey circles*) were performed at two sides of the tile drains *(dotted lines*) at different inter drain distances and at different distances from the ditch. *Grey circles* indicate locations for soil samples

groundwater levels in summer and deeper groundwater levels in winter (not shown).

The results of the N_2O measurements of the 2006–2007 experiment are presented in Fig. 2 and Table 4.

Figure 2 shows the irregular course in time of N_2O fluxes for the wet and dry fields. Peak emissions of more than 400 g N_2O–N ha^{-1} day^{-1} were measured for the dry field and of approximately 250 g N_2O–N ha^{-1} day^{-1} for the wet field. The lowest graph of Fig. 2 shows the difference in N_2O emissions between the dry and wet fields and demonstrates that most often fluxes of the dry field exceeded fluxes of the wet field, but that occasionally the reverse occurred, especially in autumn.

For the entire experimental period of 742 days, cumulative emissions equalled 56,831 ± 23,529 g N_2O–N ha^{-1} for the dry field and 18,502 ± 12,033 g N_2O–N ha^{-1} for the wet field, respectively. The majority of the N_2O emissions originated from year 1 (October 2005–October 2006) (Table 4), which was predominantly caused by the high fluxes in the fall of 2005 and summer of 2006 (Fig. 2). For the dry field the highest fluxes were obtained in winter (1 October–31 March), whereas for the wet field highest fluxes were obtained in summer (1 April–30 September, Table 4).

In general, higher N_2O–N fluxes were observed at the ditch side compared to the centre of the field. The presence of tile drains increased N_2O–N fluxes for the dry field, but had no consistent effect for the wet field. With exception of the smallest inter-drain distance (4 m) on the dry field, there were no significant differences between the different inter-drain distances on N_2O–N fluxes (Table 4).

The relation between groundwater level and N_2O loss fractions

For the entire dataset (i.e. from 1992 onwards) groundwater levels fluctuated between 0 (ponded) and 88 cm below soil surface (Table 1). Average annual groundwater levels were above target

Table 3 Selected properties of three experiments performed on the dry and wet fields of experimental farm Zegveld, The Netherlands

	Velthof et al.(1996)	Jacobs et al. (2003)	2006–2007 experiment
Experimental period	March 1992–March 1994	May 2001–June 2002	October 2005–October 2007
Method of N_2O measurement	Closed flux chambers	Closed flux chambers	Closed flux chambers
Sampling frequency	Weekly	Weekly to monthly	Monthly and after selected field activities
Replicates (# $field^{-1}$) per sampling	6	10	48

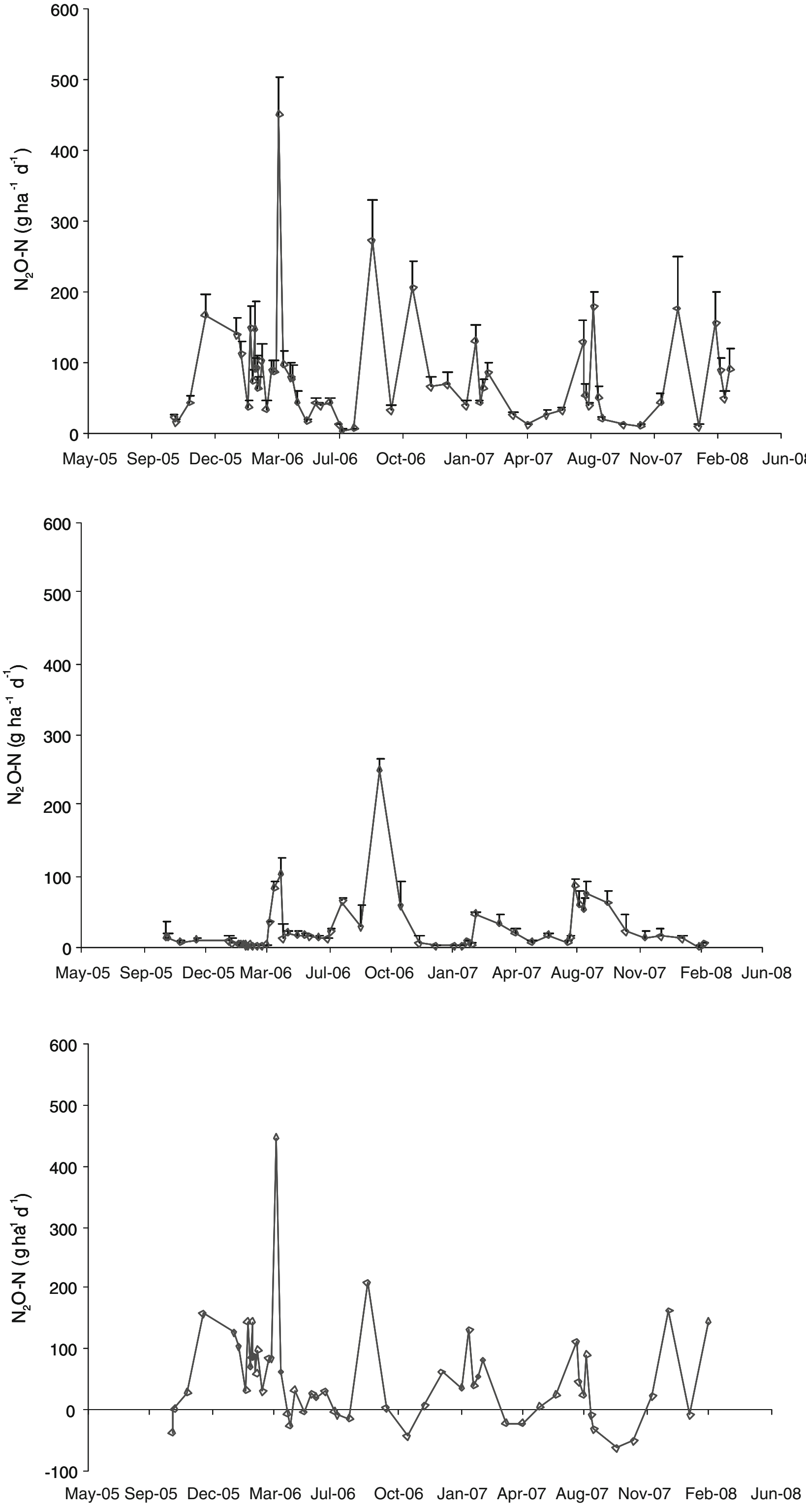

Fig. 2 Average N_2O–N emissions (±SE) from the dry field (*above*) and the wet field (*centre*) and difference between dry and wet field (*below*) for the 2006–2007 experiment

Table 4 Selected results from the two fields during 2 years (±SD) in 2006–2007

	Dry field	Wet field
Geometric mean N–N_2O flux (g ha^{-1} day^{-1})	32.29	9.67
Cumulative N–N_2O emission year 1 (kg ha^{-1} $year^{-1}$)	31.5 ± 16.1	9.8 ± 7.2
Cumulative n–N_2O emission year 2 (kg ha^{-1} $year^{-1}$)	22.8 ± 13.3	6.1 ± 6.7
Average N–N_2O flux winter half year (g ha^{-1} day^{-1})	97.88[a]	7.35[a]
Average N–N_2O flux summer half year (g ha^{-1} day^{-1})	55.33[b]	45.77[b]
Average N–N_2O flux from ditch side (g ha^{-1} day^{-1})	90.75[a]	32.89[a]
Average N–N_2O flux from centre of field (g ha^{-1} day^{-1})	67.50[b]	25.60[b]
Average soil N–NO_3 content (kg ha^{-1} ± SD)	28 ± 14	24 ± 17
Average soil N–NH_4 content (kg ha^{-1} ± SD)	16 ± 10	16 ± 9
Inter drain distance (g ha^{-1} day^{-1})		
4 m	95.13[a]	30.65[a,b]
8 m	80.04[b]	22.09[a,b]
12 m	91.15[b]	21.77[b]
Control (no drains)	51.47[c]	39.38[a]

Where appropriate *T*-tests were performed within columns separated by dashed lines and different superscripts within columns refer to significant differences ($P < 0.01$)

groundwater levels and equalled 21 cm below soil surface for the wet field and 37 cm below soil surface water for the dry field. Mean annual groundwater levels differed between the years (Table 1) due to differences in meteorological conditions. Cumulative annual N_2O emissions ranged between 7 and 39 kg N ha^{-1} $year^{-1}$ and annual N_2O emissions of the dry fields were approximately three times higher than the annual N_2O emissions from the wet fields (Table 2). Total N inputs through fertilizer, manure and dung and urine of grazing cattle ranged between 197 and 713 kg N ha^{-1} $year^{-1}$ (Table 2). Annual N_2O–N emissions as percentage of total N inputs ranged between 2 and 10% and were generally higher in the dry fields compared to the wet fields (Table 2). There was no significant relation between average annual groundwater levels and N_2O emissions, but expressed as fraction of total N inputs according to Eq. 3 the N loss fraction was significantly ($R^2_{adj} = 0.74$, $P < 0.001$) related to groundwater level, i.e. lower groundwater levels resulted in higher relative emissions (Fig. 3).

To calculate the N_2O emission from grazed peat lands as function of total N inputs and groundwater level, the regression equation of Fig. 3 was rewritten to:

$$N_2O - N = 0.0027 \cdot GWL \cdot N_{input} - 0.020 \cdot N_{input} \quad (4)$$

where N_2O–N is the annual N_2O–N emission (kg N ha^{-1} $year^{-1}$), GWL is the annual average groundwater level (cm below soil surface) and N_{input} is the total N input via fertilizers, manure and cattle dropping (kg ha^{-1} $year^{-1}$). In Fig. 4 the two official methodologies (Tier 1 and Tier 2) to estimate direct N_2O–N emissions from cultivated and managed organic soils are visualized supplemented with the results of Eq. 3 using groundwater levels of −20 and −40 cm and assuming 1/3 of the total N input originating from mineral fertilizers, 2/9 from manure and 4/9 from dung and urine of grazing cattle according to current practices at this site (Table 2).

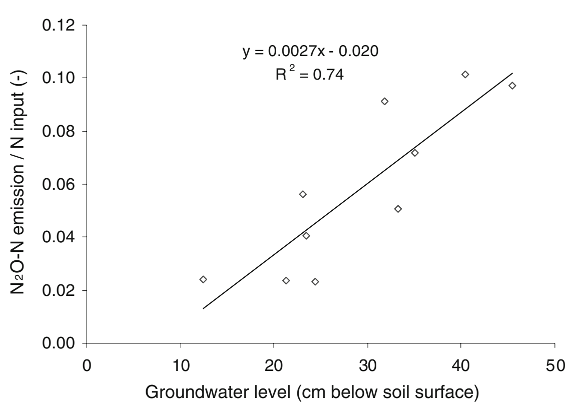

Fig. 3 Yearly average groundwater level and N_2O–N loss fraction for all experiments on wet and dry fields of experimental farm Zegveld. Nitrogen inputs refer to all inputs through grazing cattle, mineral and organic fertilizers. *Line* shows linear regression between groundwater levels (GWL) and N_2O losses ($P < 0.001$)

Discussion

Groundwater level and N_2O emissions

Although the differences in groundwater level between the wet and dry fields were basically small, i.e. for many parts of the world, any field with a groundwater level within 1 m below soil surface would still be classified as 'wet', the 'wet' and 'dry' fields showed clearly different N_2O emissions. The annual N_2O emissions from the dry fields were about three times higher than the emissions from the wet fields (Table 2). This could not be related to differences in soil NO_3 contents (Table 4). However, soil samples were taken from the upper 20 cm and Van Beek et al. (2004) suggested that denitrification (which is a major source of N_2O) is strongly related to soil NO_3 contents just above the groundwater level, i.e. close to anaerobic and aerobic alternations. Then, in the wet field N_2O production was likely to be limited by NO_3 contents and when groundwater levels dropped in summer nitrification could release NO_3 and denitrification, and N_2O emission, could set-off. This mechanism implies an optimal (in stead of a minimum or maximum) groundwater level under which N_2O emissions are maximal. Such an optimum groundwater level was indeed proposed by Velthof (1997). This mechanism also explains that for the wet

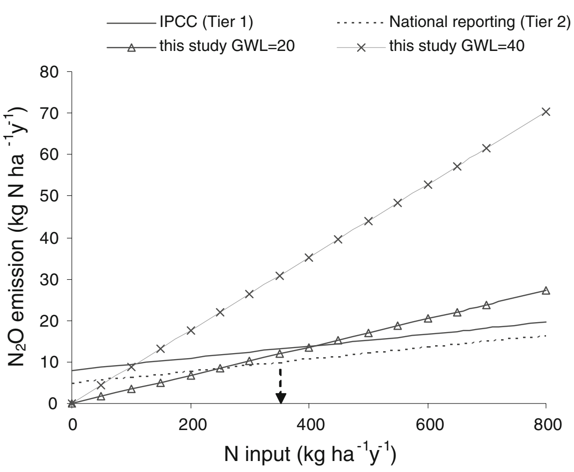

Fig. 4 Calculated annual N_2O–N emissions using methodologies from the IPCC (Tier 1), national reporting (Tier 2) and results found in this study for groundwater levels of 20 and 40 cm below soil surface (Eq. 3). *Dotted arrow* indicates average N input during 5 years according to Table 2

field higher N_2O emissions were observed in summer, whereas for the dry field higher N_2O emissions were observed in winter (Table 4). However, Velthof et al. (1996) found for both fields higher N_2O emissions in summer, but in their study the wet field received considerably more N inputs than in the most recent years (Table 2) which may have altered the seasonal effects.

Both fields were intensively grazed and N inputs through droppings from grazing cattle ranged from 75 to 269 kg ha^{-1} year^{-1} (Table 2). Grazing generally increases the N_2O emissions from grasslands because of additional N inputs (Velthof and Oenema 1995a) and through the formation of hot-spots for N_2O emission (Oenema et al. 1997). Velthof and Oenema (1995a) reported an average 'base' N_2O emission, i.e. N_2O emissions from unfertilized and mown plots, of 2.0 kg ha^{-1} year^{-1} for a field from the wet block and 8.6 kg ha^{-1} year^{-1} for a field from the dry block. Consequently, using the data of Table 2, field management including grazing increased the emission of N_2O with almost a factor 6 for the wet fields and with a factor 3.5 for the dry fields. Hence, the N_2O emission as fraction of total N input was lower for the wet fields compared to the dry fields (Table 2), but the relative increase of N_2O emission as a result of fertilization and grazing was higher on the wet fields compared to the dry fields.

Through the presence of tile drains, groundwater level fluctuations decreased. Fluctuations in groundwater levels may increase the emission of N_2O through the alterations in anaerobic and aerobic conditions. Consequently, it was expected that tile drainage would decrease N_2O emissions. This was, however, not observed and the dry field had even higher N_2O emissions when drained (Table 4). Hence, tile drainage did not contribute to the reduction of N_2O emission from managed peat soils.

Different methods to estimate N_2O emission from managed peat soils

The IPCC emission factor for organic, managed soils like in the present study equals 13 kg N–N_2O ha^{-1} year^{-1} using Eq. 2 and an average total N input of 380 kg N ha^{-1} year^{-1} (Table 2). This is a reasonable estimate for the wet fields, but underestimates the N_2O emission from the dry fields. The IPCC (2006) reports an uncertainty range of 2–24 kg N–

N_2O ha^{-1} year^{-1} which still underestimates annual N_2O–N emissions of the dry fields for most of the years (Table 2). For the national reports towards the IPCC The Netherlands uses the Tier 2 approach which yields an estimated emission of 10 kg N ha^{-1} year^{-1} for a total N input of 380 kg N ha^{-1} year^{-1}. The national approach is based on the study of Kuikman et al. (2005) and uses long-term subsidence data (C loss), C/N ratios of organic matter and an N_2/N_2O ratio of 2%. Especially this last conversion is weakly supported by experimental data, but is the best available estimate of this moment and is based on the emission factor of 2% for animal excreta. All official approaches underestimate N_2O–N emissions from the dry fields. In The Netherlands the groundwater levels used in this study are commonly found for cultivated peat soils. So far, groundwater level is not part of any methodology to estimate N_2O emissions from cultivated and managed peat soils. The results of Fig. 2 demonstrate that N_2O losses increase with decreasing groundwater levels and Fig. 3 shows considerable underestimation of annual N_2O–N losses for the IPCC and the Dutch national reporting methodologies, especially for the dry fields.

Comparison with other studies

Compared to other studies on N_2O emission from cultivated organic soils, we found relatively high emission rates. This is probably related to the high N application rates and the relatively warm (i.e. temperate) climate. Notably, most studies on N_2O emissions from managed organic soils originate from extensively managed systems in boreal climate zones. For example, Von Arnold et al. (2005) reported annual N_2O–N emission rates of less than 1 kg ha^{-1} for organic soils in Sweden that were used for forestry and did not receive fertilizer N. Maljanen et al. (2004) reported annual N_2O–N emissions of 2.8 kg N ha^{-1} for grassland on peat soil and Nykanen et al. (1995) found an annual N_2O emission of 8–9 kg N_2O–N ha^{-1} for organic grassland soils in Finland. Regina et al. (2004) reported N_2O–N emissions of 7.3 ± 1.2 kg N ha^{-1} year^{-1} for fertilized grassland on peat soil in the South of Finland. These authors suggested that an emission factor of 10.4 kg N ha^{-1} year^{-1} be used for managed peat soils and that effects from events of fertilizer application be omitted, because more than 50% of the annual N_2O emission occurred outside the growing season (October–April). The latter is also true for our site, where approximately 50% of the annual N_2O emission occurred in winter. Nevertheless, still there was an effect of fertilizer input on annual N_2O emission (Fig. 2). The effect of N input on annual N_2O emission was confirmed by Smith et al. (1998) for Scottish grassland on peat soil. We argue to include N application rates and groundwater levels in methodologies to estimate N_2O emissions from cultivated and managed organic soils for optimal reflection of driving forces of N_2O emissions from these soils.

Conclusions

There is a tendency towards raising groundwater levels in the Western peat land area of The Netherlands. Raising groundwater levels most likely results in lower cumulative N_2O–N emissions as N_2O–N losses per kg of N input are expected to decrease by 0.27% per cm groundwater level rise, under unchanged field management. At present, official reports presumably underestimate the emissions of N_2O from grazed grasslands on peat soils. Official calculation procedures account for the application of N to soil, but neglect differences in groundwater level, whilst differences in groundwater level may affect N_2O emission factors fivefold. We argue that the observed relation between mean annual groundwater level and relative N_2O emissions should be included in the Dutch national reporting methodology on greenhouse gas emission to derive accurate estimations of annual N_2O emissions from grazed grasslands on organic soils.

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References

Bussink DW (1994) Relationships between ammonia volatilization and nitrogen application rate, intake and excretion of herbage nitrogen by cattle on grazed swards. Fert Res 38:111–121

de Klein C, Novoa RSA, Ogle S, Smith KA, Rochette P, Wirth TC, McConkey BG, Mosier A, Rypdal K (2006) Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea Application. 2006 IPCC Guidelines for National Greenhouse Gas Inventories

Flessa H, Wild U, Klemisch M, Pfadenhauer J (1998) Nitrous oxide and methane fluxes from organic soils under agriculture. Europ J Soil Sci 49:327–335

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA

IPCC (2006) IPCC guidelines for national greenhouse gas inventories, vol 4. Agriculture, forestry and other land use, chap. 11

Jacobs CMJ, Moors EJ, van der Bolt FJE (2003). Effect of water management on greenhouse gas emissions in the peat land area at ROC Zegveld. Alterra report 840

Kuikman PJ, van den Akker JJH and de Vries F (2005) Emission of N_2O and CO_2 from organic agricultural soils. Alterra report 1035.2

Maljanen M, Komulainen VM, Hytonen J, Martikainen P, Laine J (2004) Carbon dioxide, nitrous oxide and methane dynamics in boreal organic agricultural soils with different soil characteristics. Soil Biol Biochem 36:1801–1808

Nykanen H, Alm J, Lang K, Silvola J, Martikainen PJ (1995) Emissions of CH_4, N_2O and CO_2 from a virgin fen and a fen drained for grassland in Finland. J Biogeogr 22:351–357

Oenema O, Velthof GL, Yamulki S, Jarvis SC (1997) Nitrous oxide emissions from grazed grassland. Soil Use Man 13:288–295

Pleijter M, van den Akker JJH (2007) Infiltration drains in peat land area. Alterra report 1586

Regina K, Syvasalo E, Hannukkala A, Esala M (2004) Fluxes of N_2O from farmed peat soils in Finland. Europ J Soil Sci 55:591–599

Smith KA, McTaggart IP, Dobbie KE, Conen F (1998) Emissions of N_2O from Scottish agricultural soils, as a function of fertilizer N. Nutr Cycl Agroecosyst 52:123–130

Tiedje J, Sexstone A, Parkin T, Revsbech N, Shelton D (1984) Anaerobic processes in soil. Plant Soil 76:197–212

van Beek CL, Brouwer L, Oenema O (2003) The use of farmgate balances and soil surface balances as estimator for nitrogen leaching to surface water. Nutr Cycl Agroecosyst 67:233–244

van Beek CL, Hummelink EWJ, Velthof GL, Oenema O (2004) Nitrogen losses through denitrification form an intensively managed grassland on peat soil. Biol Fert Soils 39:329–336

van der Hoek KW, van Schijndel MW, Kuikman PJ (2007) Direct and indirect nitrous oxide emissions from agricultural soils, 1990–2003 Background document on the calculation method for the Dutch National Inventory Report. RIVM report 680125003/2007

van Groenigen JW, Kasper GJ, Velthof GL, van den Pol-van Dasselaar A, Kuikman PJ (2004) Nitrous oxide emissions from silage maize fields under different mineral nitrogen fertilizer and slurry applications. Plant Soil 263:101–111

Velthof GL (1997) General Discussion PhD thesis Nitrous oxide emission from grazed grasslands. Wageningen University

Velthof GL, Oenema O (1995a) Nitrous oxide fluxes from grassland in the Netherlands: II. Effects of soil type, nitrogen fertilizer application and grazing. Europ Journal Soil Sci 46:541–549

Velthof GL, Oenema O (1995b) Nitrous oxide fluxes from grassland in the Netherlands: I. Statistical analysis of flux chamber measurements. Europ J Soil Sci 46:533–540

Velthof GL, Brader AB, Oenema O (1996) Seasonal variations in nitrous oxide losses from managed grasslands in The Netherlands. Plant Soil 181:263–274

von Arnold K, Nilsson M, Hanell B, Weslien P, Klemedtsson L (2005) Fluxes of CO_2, CH_4 and N_2O from drained organic soils in deciduous forests. Soil Biol Biochem 37:1059–1071

Wrage N, Velthof GL, van Beusichem M, Oenema O (2001) Role of nitrifier denitrification in the production of nitrous oxide. Soil Biol Biochem 33:1723–1732