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Emissions of nitrous oxide from boreal agricultural mineral soils—Statistical models based on measurements

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ABSTRACT

This study compiles data of nitrous oxide (N_2O) emissions from 13 fields on mineral soils in Finland with differing soil type, crop and management. Measurements using the chamber technique were conducted for periods of 1–3 years on each field in 2000–2009. The annual emissions varied between 0.12 and 12 kg N_2O-N ha^{-1} yr^{-1} and the emission rates were higher for annual compared to perennial crops. Statistical mixed models were derived based on the measured emissions of N_2O and background variables. Environmental and management data available for the analysis were the crop, fertilizer rate, type of fertilizer, soil characteristics and weather data. Models with the fertilizer rate and type of crop (annual/perennial) as variables were selected as the simplest method to estimate the flux of N_2O from mineral agricultural soils. The effect of fertilizer type (mineral/organic) can be added to obtain a more detailed model. In the case of manures, the amount of mineral nitrogen was better related to N_2O flux than the amount of total nitrogen. These models give realistic estimates of N_2O fluxes in boreal conditions with frozen soils in the winter, frequently renewed grasslands and spring-sown crops as majority of the annual crops.

1. Introduction

Nitrous oxide (N_2O) is a greenhouse gas with a high global warming potential and the ability to destruct ozone molecules in the atmosphere (IPCC, 2007). Cultivated soils are one of the most important sources of N_2O. The uncertainty of this emission source is remarkably high due to high spatial and temporal variation (Snyder et al., 2009) which hampers any attempt to calculate a national or even a field scale estimate for these emissions. The microbial processes most contributing to the emissions of N_2O from soils are nitrification in aerobic conditions and denitrification in anaerobic conditions (Focht and Verstraete, 1977). Factors affecting the emission rate are for example nitrogen, carbon and oxygen content of the soil as well as pH and temperature (Granli and Bøckman, 1994). These emissions are reported in the national inventories of greenhouse gases (Lokupitiya and Paustian, 2006) and their mitigation is part of global and local climate policies worldwide. Intensive agricultural production with the aim of producing proper yields with minimum losses of nutrients to waters and atmosphere is generally considered as the best way of avoiding high N_2O fluxes (Snyder et al., 2009).

As there is high variation in the variables regulating N_2O fluxes in time and between sites, estimating the annual emission rate would demand detailed modelling using simulation models (Chen et al., 2008). Often detailed modelling, however, is not possible due to lack of data on the background variables. Thus there is a need for simple models that can be used to produce an estimate of the annual emission rate using data that is readily available. The emissions of N_2O have been found to be strongly related to the fertilizer rate (Bouwman, 1996; Bouwman et al., 2002; Stehfest and Bouwman, 2006). A simple method has been developed for estimating the effect of fertilizer rate on N_2O emissions (IPCC, 2006). The emission factor adopted by the IPCC is 0.01 indicating that 1% of the applied fertilizer N is assumed to be emitted as N_2O-N to the atmosphere. The review by Stehfest and Bouwman (2006) compiled data in global scale and they derived equations for different combinations of factor classes based on differences in soil C content, pH, texture, climate and crop type. European data were compiled by Freibauer and Kaltschmitt (2003) and in the resulting statistical models soil texture and carbon or nitrogen content explained part of the variation in N_2O emissions in addition to the fertilizer rate.

In the above-mentioned studies data from boreal agricultural soils have been scarce. Boreal conditions with winter-time frost and short growing season differ from other climate regions with possible consequences on the emission rates of N_2O. The aim of this study was to summarize the results of national full-year flux measurements of N_2O from mineral agricultural soils during the

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Table 1
Measured annual N_2O emissions and background data.

Field	N_2O-N (kg ha^{-1})	Crop	C (%)	N (%)	Sand (%)	Clay (%)	Fert. N (total) (kg ha^{-1})	Fert. N (min) (kg ha^{-1})	Fert. type	Reference
1	1.7 ± 0.4	Grass	2.4	0.16	85	9.7	225	225	Min	Syväsalo et al. (2004)
	5.6 ± 3.6	Barley	2.4	0.16	85	9.7	100	100	Min	Syväsalo et al. (2004)
2	3.8 ± 1.2	Grass	2.9	0.22	15	57	225	225	Min	Syväsalo et al. (2004)
	4.0 ± 0.9	Barley	2.9	0.22	15	57	100	100	Min	Syväsalo et al. (2004)
3	1.2 ± 0.6	Grass	5.0	–	75	5.0	218	218	Min	Syväsalo et al. (2006)
	1.4 ± 0.4	Grass	5.0	–	75	5.0	130	0	Org[a]	Syväsalo et al. (2006)
	3.5 ± 0.5	Rye	5.0	–	75	5.0	110	110	Min	Syväsalo et al. (2006)
4	2.6 ± 2.4	Grass	2.0	0.18	14	54	150	150	Min	Regina et al. (2006)
	0.5 ± 0.7	Grass[b]	2.4	0.18	14	58	0	0	–	Regina et al. (2006)
5	0.7 ± 0.3	Grass	3.8	0.27	15	76	128	128	Min	Petersen et al. (2006)[c]
	1.8 ± 0.5	Barley	3.8	0.27	15	76	80	80	Min	Petersen et al. (2006)
	2.7 ± 0.1	Rye	3.8	0.27	15	76	118	118	Min	Petersen et al. (2006)
	1.4 ± 0.4	Oat + pea	3.8	0.27	15	76	53	53	Min	Petersen et al. (2006)
	0.4 ± 0.04	Grass	4.6	0.32	15	76	0	0	–	Petersen et al. (2006)
	5.5 ± 1.0	Barley	4.6	0.32	15	76	160	80	Org	Petersen et al. (2006)
	1.9 ± 0.06	Rye	4.6	0.32	15	76	280	100	Org	Petersen et al. (2006)
	1.3 ± 0.07	Oat + pea	4.6	0.32	15	76	0.25	0	Org[a]	Petersen et al. (2006)
6	3.1 ± 1.2	Barley	2.8	0.21	26	46	104	104	Min	Unpublished
7	4.3 ± 1.3	Barley	2.8	0.23	19	62	106	106	Min	Unpublished
8	6.4 ± 0.8	Barley	3.2	0.25	18	48	105	105	Min	Unpublished
	5.3 ± 0.4	Rapeseed	3.2	0.25	18	48	105	105	Min	Unpublished
9	7.9 ± 1.9	Barley	2.5	0.16	51	19	85	85	Min	Unpublished
10	2.6 ± 1.1	Barley	2.5	–	75	18	100	100	Min	Regina and Perälä (2006), Kapuinen and Regina (2010)[d]
	3.9 ± 1.5	Barley	2.5	–	75	18	90–130	20–85	Org	Regina and Perälä (2006), Kapuinen and Regina (2010)[d]
11	4.0 ± 0.8	Barley	2.0	–	74	19	100	100	Min	Kapuinen and Regina (2010)[d]
	3.6 ± 1.7	Barley	2.0	–	74	19	95–150	90	Org	Kapuinen and Regina (2010)[d]
	2.6 ± 1.2	Barley	2.0	–	74	19	200–300	90	Org	Kapuinen and Regina (2010)[d]
12	1.2 ± 0.1	Barley	5.1	–	31	60	100	100	Min	Kapuinen and Regina (2010)[d]
	2.3 ± 0.9	Barley	5.1	–	31	60	100–150	95	Org	Kapuinen and Regina (2010)[d]
	1.4 ± 0.6	Barley	5.1	–	31	60	200–450	90	Org	Kapuinen and Regina (2010)[d]
13	2.0 ± 1.5	Grass	3.0	–	13	56	180	180	Min	Perälä and Regina (2006), Kapuinen et al. (2007)[d]
	2.0 ± 1.4	Grass	3.0	–	13	56	180–260	130–170	Org	Perälä and Regina (2006), Kapuinen et al. (2007)[d]

If the measurements lasted more than one year the mean flux is the mean of all years.

[a] Nitrogen fixation.

[b] Buffer zone.

[c] Mean of the crop rotation was published, here we present values for each crop.

[d] Description of experimental setup only.

last decade and to develop statistical models for estimating these fluxes.

2. Materials and methods

Data from gas flux measurements on 13 fields on mineral soils in southern and central Finland were included in the analysis. The fields were located between latitudes 61 and 63 and they all were either in cereal cultivation, crop rotation or in grass cultivation. The data consists of 275 estimates of annual fluxes from measuring points covering a 60 cm × 60 cm area. The method of measurement has been similar in all studies and the details of the measurements can be found in the original publications (Table 1). The calculation of the annual flux was based on measurements done 1–4 times per month and linear interpolation between the measurements. Data for the background variables consisted of the fertilizer rate, type of fertilizer (mineral/organic), percentage of organic carbon, total nitrogen, sand and clay in the 0–20 cm soil layer, mean temperature of the winter months (January–March), total precipitation of the summer months (May–September) and crop type (perennial/annual). The crops receiving organic fertilizers may have had part of the applied nitrogen as mineral fertilizer but most of the nitrogen was given as manure. All types of organic fertilizers (farmyard manure, slurries, sewage sludge and green manure) were treated as one group. All of the fields with annual crops were ploughed in the autumn. None of the grass fields were grazed, however, there was grazing on field 4 but our chamber sites were fenced. None of the grass fields but the buffer zones of field 5 were long-term grasslands which means that the age of the grass crop was three years at maximum.

The data were analysed using the mixed model REML estimation method of SAS/MIXED software (version 9.3). The values for N_2O fluxes were log-transformed to normalise their distribution. The observations were not totally independent as some of the annual fluxes were either obtained from different locations of a certain field or from measurements from the same field in consecutive years. Therefore field and year were added as random effects in the models. The degrees of freedom were computed by the Kenward–Roger method (Kenward and Roger, 1997). At first, we included all background variables in the model as fixed variables to find the most significant ones. All significant variables were kept in the models. The model which the analyses were based on was the following

$$y_{ijklm} = \mu + \mathrm{Fi}Y_{lm} + C_i + \mathrm{Fe}_j + \mathrm{N}_k + \mathrm{CN}_{ik} + \mathrm{FeN}_{jk} + \varepsilon_{ijklm} \quad \text{(model 2; the others are variants of this)}$$

where μ is the overall mean, C_i, Fe_j and N_k are the fixed effects of the crop, fertilizer and total nitrogen, respectively. Two-factor interactions were also included in the model. The variables of Fi_l, Y_m and ε_{ijklm} are the random effects of the field, year and residual error. All the random effects were assumed to be mutually independent. The normality assumption of the residuals was checked by using the box plot (Tukey, 1977). Statistical differences were tested using the Tukey–Kramer method. The confidence intervals were determined as predictions of the lower and upper bounds of the model estimates. Emission factors comparable to the IPCC default factor for each model were determined by subtracting the intercept from the modelled flux rate and dividing this value by the fertilizer rate. The mean emission factors for fertilizer rates 80–200 kg ha^{-1} are presented.

Table 2
Solutions for fixed effects of the models.

Model	Effect	Estimate	SE	DF	P
1	Intercept	−0.3102	0.08827	133	0.02
	totN	0.002631	0.000386	262	<0.0001
	Annual crop	0.8992	0.09145	257	<0.0001
	totN × annual crop	−0.00289	0.00047	270	<0.0001
2	Intercept	−0.5095	0.01001	127	0.2
	totN	0.004016	0.000477	267	<0.0001
	Annual crop	0.8636	0.08872	264	<0.0001
	Org. fertilizer	0.3122	0.09105	242	0.0006
	totN × annual crop	−0.00175	0.000518	259	0.0007
	totN × org. fertilizer	−0.00261	0.000578	241	<0.0001
3	Intercept	−0.2762	0.07996	104	0.8
	minN	0.002848	0.000388	272	<0.0001
	Annual crop	0.58	0.06	149	<0.0001
4	Intercept	−0.4497	0.09949	113	0.6
	minN	0.003715	0.000467	268	<0.0001
	Annual crop	0.656	0.06516	150	<0.0001
	Org. fertilizer	0.3182	0.09481	255	0.0008
	minN × org. fertilizer	−0.00219	0.000778	245	0.0053

totN, amount of applied nitrogen as kg total nitrogen per hectare; minN, amount of applied N as kg mineral nitrogen per hectare.

3. Results

The mean annual flux of all measurements was 2.9 ± 2.0 kg N_2O-N ha^{-1} yr^{-1}. On average, the emissions of N_2O were lower from grass cultivation (1.8 ± 1.5 kg N_2O-N ha^{-1} yr^{-1}) than from cultivation of annual crops (3.5 ± 2.0 kg N_2O-N ha^{-1} yr^{-1}). The difference between annual and perennial crops was statistically significant at the level $p < 0.001$.

On the basis of the results of the mixed model analysis, we selected four relatively simple models as the most practical way of estimating emissions of N_2O from agricultural soils. Model 1 is based on the division between two crop types, perennial grasses and annual crops, together with the annual amount (kg) of nitrogen (mineral or organic) applied on the field (Table 2). In this case, the emissions from grass cultivation can be estimated adding the effect of fertilization to a background emission of N_2O. Amount of fertilizer nitrogen applied annually is given as total amount with both mineral and organic forms included. The emissions from annual crops can be estimated adding the effect for annual crop as well as the interaction of fertilizer and crop. The equations yield the logarithmic value of the N_2O flux and thus the result has to be back-transformed to the emission value as kg of N_2O-N. According to the tests of fixed effects all of the model components were statistically significant at the level $p < 0.002$. The emission factors based on model 1 results were 0.5% for grasses and −0.2% for annual crops (Table 3).

In model 2, the amount of total nitrogen is used as input as in model 1 but the effect of fertilizer type is added to the model. In this case there are separate equations for perennial and annual crops fertilized with mineral fertilizer but also equations for these crops if they are fertilized using organic fertilizer (Table 2). The effect of organic fertilizer is added to the equation together with the interaction of organic fertilizer and the fertilizer rate. All effects in the equations except the intercept were statistically significant at the level $p < 0.001$ at minimum. Emission factors for model 2 were 0.2–0.5% for perennial and −0.4% to 1.6% for annual crops (Table 3).

Model 3 is the simplest model and close to model 1 but the amount of mineral nitrogen in manures is needed as an input parameter (Table 2). In this case there is a background emission together with the effect of applied mineral nitrogen for estimating emissions from perennial crops. For annual crops, the effect of annual crop has to be added. The effects were statistically significant at level $p < 0.0001$ except the intercept. Emission factors calculated from the results of this model were 0.5% for perennial and 2.0% for annual crops (Table 3).

Model 4 is comparable to model 2 with the differentiation to annual and perennial crops as well as organic and mineral fertilizer types but the amount of mineral nitrogen in the manures or other organic fertilizers has to be known (Table 2). The model effects except the intercept were statistically significant at the level of $p < 0.005$ at minimum. The calculated emission factors were 1.1–1.4% for perennial crops and 4.8–6.3% for annual crops (Table 3).

Table 3
Equations for estimating N_2O flux from agricultural soils.

Model	Crop type	log N_2O-N (kg ha^{-1} yr^{-1})	EF (%)
1	Perennial	=−0.3102 + 0.002631 × totN	0.5
	Annual	=−0.3102 + 0.002631 × totN + 0.8992 − a	−0.2
2	Perennial with mineral fertilizer	=−0.5095 + 0.004016 × totN	0.5
	Perennial with organic fertilizer	=−0.5095 + 0.004016 × totN + 0.3122 − b	0.2
	Annual with mineral fertilizer	=−0. 5095 + 0.004016 × totN + 0.8636 − c	1.6
	Annual with organic fertilizer	=−0. 5095 + 0.004016 × totN + 0.8636 + 0.3122 − d	−0.4
3	Perennial	=−0.2762 + 0.002848 × minN	0.5
	Annual	=−0.2762 + 0.002848 × minN + 0.58	2.0
4	Perennial with mineral fertilizer	=−0.4497 + 0.003715 × minN	1.1
	Perennial with organic fertilizer	=−0.4497 + 0.003715 × minN + 0.3182 − e	1.4
	Annual with mineral fertilizer	=−0.4497 + 0.003715 × minN + 0.656	4.8
	Annual with organic fertilizer	=−0.4497 + 0.003715 × minN + 0.656 + 0.3182 − e	6.3

totN, amount of applied nitrogen as kg total nitrogen per hectare; minN, amount of applied N as kg mineral nitrogen per hectare; EF, mean emission factor calculated for fertilizer rates 80–200 kg ha^{-1}. Effects of interactions: a = 0.00298 × totN; b = 0.00261 × totN; c = 0.00175 × totN; d = 0.00175 × totN + 0.00261 × totN; e = 0.00219 × minN.

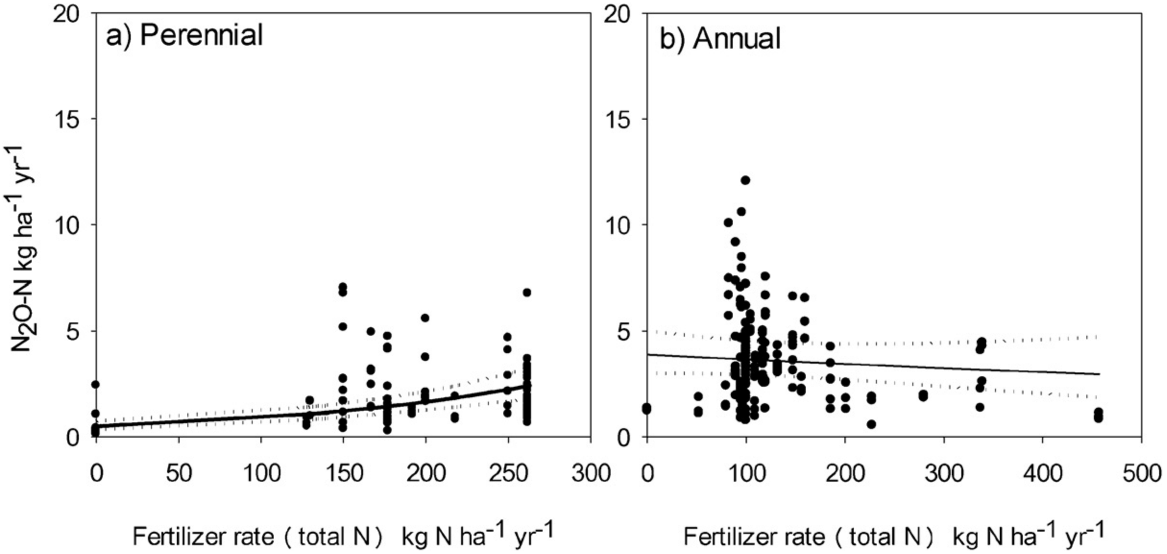

Fig. 1. Measured N_2O emissions and results for model 1 on mineral soils with perennial (a) and annual (b) crops. Dotted lines denote the 95% confidence interval.

4. Discussion

The mean annual N_2O flux of 2.9 kg N ha^{-1} yr^{-1} was in accordance with the results for German croplands and grasslands (Dechow and Freibauer, 2011) or eastern Canadian conditions (Gregorich et al., 2005) representing similar climatic conditions to ours. The results indicate that the most important factor determining the annual flux of N_2O is the type of crop based on the division between annual and perennial crops. The large difference between annual and perennial crops is mainly a consequence of the long non-vegetated period of the fields used for growing annual crops. In spring-sown crops the period when the soils are not covered by living crops can be close to 9 months which increases the risk of N_2O emissions from these soils. All cereal fields in this study except rye on field 5 were ploughed in the autumn and sown in the spring, a practice that maximizes the non-vegetated period. According to the agricultural statistics, autumn-sown cereals are a minority (<10%) of the cereal crops in Finland and half of the total cultivated area has no crop cover during the winter. The grass crops take up nutrients for a longer period annually than the annual crops which decreases the amount of nitrogen available for the processes leading to gaseous losses of nitrogen. In addition, less frequent ploughing (approximately every fourth year) may reduce the availability of mineral nitrogen due to less mineralization of the organic matter in the soil. Mouldboard plough in the autumn was found to increase the N_2O fluxes of annual crops in the winter in the data compilation by Gregorich et al. (2005). In our data, the difference of annual and perennial crops was also reflected in the proportion of N_2O flux emitted during the winter period (October–March) so that for annual crops the proportion of the winter flux was 45% of the annual flux whereas for perennial crops it was 33% (data not shown).

The fertilizer rate explained part of the variation in N_2O emissions as found in most similar studies (Freibauer and Kaltschmitt, 2003; Gregorich et al., 2005; Stehfest and Bouwman, 2006). In most models there was as a clearly increasing trend of emissions with increasing fertilizer rate. The results for model 1 (annual crops) and model 2 (annual with organic fertilizer) were consistent with the reported high base level flux and small effect of fertilizer on croplands in a German study (Dechow and Freibauer, 2011). However, the results shown in Figs. 1b and 3b show that having the amount of mineral nitrogen in the model instead of total nitrogen for the same measurement dataset gives a better response between N_2O fluxes and fertilizer rate. In this study, the highest fertilizer rates were given as organic fertilizers with a low proportion of soluble nitrogen. Thus, the amount of total nitrogen did not reflect well the amount available for denitrifiers in the soil. However, in the normal range of fertilizer rates (80–120 kg ha^{-1}) our model 1 also gives realistic estimates of the emissions. Our results are in line with the findings of Dechow and Freibauer (2011) who also found a different response to fertilization by grasslands and croplands. Emission factors calculated from this dataset are close to the IPCC default of 1% in the case of perennial crops but in general higher for annual crops. There was, however, high deviation in these values.

The results of models 2 and 4 suggest that organic fertilizers do not cause a higher emission rate than mineral fertilizers (Figs. 2 and 4) although manure slurries may enhance denitrification by increasing soil moisture and providing an additional carbon source (Snyder et al., 2009). In addition, all organic nitrogen may not be available to the crop during the crop growth and the amount of residual nitrogen in the soil after harvest may be substantial. The nitrogen recovery rate of organic fertilizer can be half of that of the mineral fertilizers (Nannen et al., 2011). However, we did not observe remarkably higher winter-time emissions from fields with organic fertilizers as could be predicted with high amount of residual nitrogen. The proportion of the annual flux emitted during the winter was 41% for the fields fertilized with organic fertilizers and 39% for fields receiving only mineral fertilizer. There may be differences between the types of mineral fertilizers and the emissions are thought to increase in the order nitrate < ammonium < urea (Harrison and Webb, 2001; Bouwman et al., 2002; Tenuta and Beauchamp, 2003). However, that aspect was not considered here since the only type of fertilizer used was ammonium nitrate. Ammonium nitrate is the most common mineral fertilizer type in Finland and urea is practically not used.

There were many background variables that were available but did not improve the performance of the models. We have observed that the conditions during the winter have a strong effect on the amount of N_2O emitted from frozen soils. Especially in southern Finland it is common to have partial thawing of the frost which often induces high emissions as observed also by Freibauer and Kaltschmitt (2003) and Jungkunst et al. (2006). Since more than half of the annual emissions are often emitted during the period outside the growing season (Röver et al., 1998; Teepe et al., 2001; Syväsalo

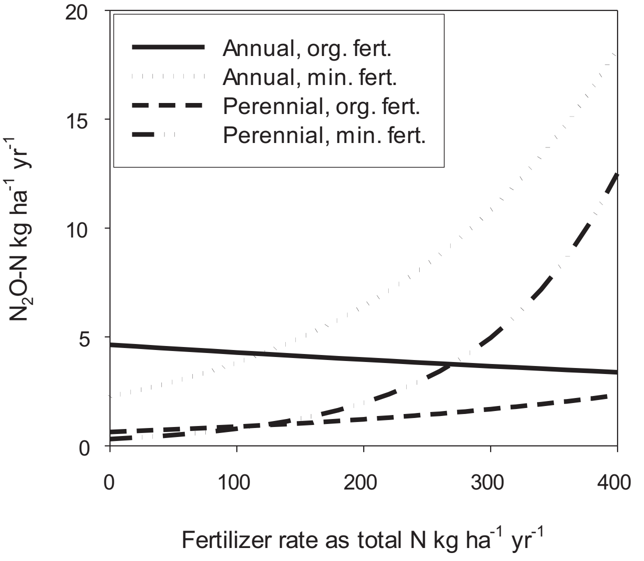

Fig. 2. Model 2 results for perennial and annual crops either with mineral or organic fertilizers.

et al., 2004, 2006) the weather conditions during the winter could potentially have an effect on the annual total. We also tested the possibility to use summer time precipitation as a model variable since high precipitation could increase denitrification activity in soils. However, neither the mean winter temperature nor precipitation during the summer proved useful as a model parameter in this dataset. In a dataset including measurements from several different climate zones Dechow and Freibauer (2011) found that winter temperature affected the fluxes. Even if the winter temperature did not explain the annual flux rate the proportion of winter flux was the greater the higher was the mean temperature of the period from January to March ($r = 0.317$, $p < 0.001$) indicating that a mild winter can enhance N_2O fluxes during this period but the effect on the annual flux values was not evident.

Soil texture regulates the soil aeration status and thus could affect the N_2O emissions as found in some studies (Freibauer and Kaltschmitt, 2003) but in this study sand or clay content of the soil did not explain the variation in annual N_2O fluxes. Soil carbon content has been found to affect the rate of N_2O emissions e.g. in the global data compilation by Stehfest and Bouwman (2006) as well as in laboratory analysis (Jäger et al., 2011) but in our data the range of carbon contents was maybe too narrow to allow its use as a model variable. If organic soils were included in the analysis the range of carbon contents would be wider and probably a clear relation between the carbon content and N_2O emissions would be found. However, we did not consider including measurement results from organic soils in this analysis since there the regulation of fluxes differs from mineral soils. It is also possible that the total amount of soil carbon does not well enough predict the amount of carbon available for denitrifiers since most carbon stored in soils is not easily degradable.

The estimates given by the different models were in relatively good agreement at certain selected typical fertilizer rates (Table 4). However, if using these equations for upscaling N_2O emissions the high uncertainties due to lack of data must be kept in mind especially in the case of the highest fertilizer rates (Figs. 1 and 3). Since we aimed at a calculation method for mineral agricultural soils, other available national data e.g. from organic soils or forest soils was not included in this analysis. Greenhouse gas emission measurements from agriculture in the boreal region are scarce since agriculture is mainly practiced in warmer regions. For these reasons, the national dataset was limited to these measurement results.

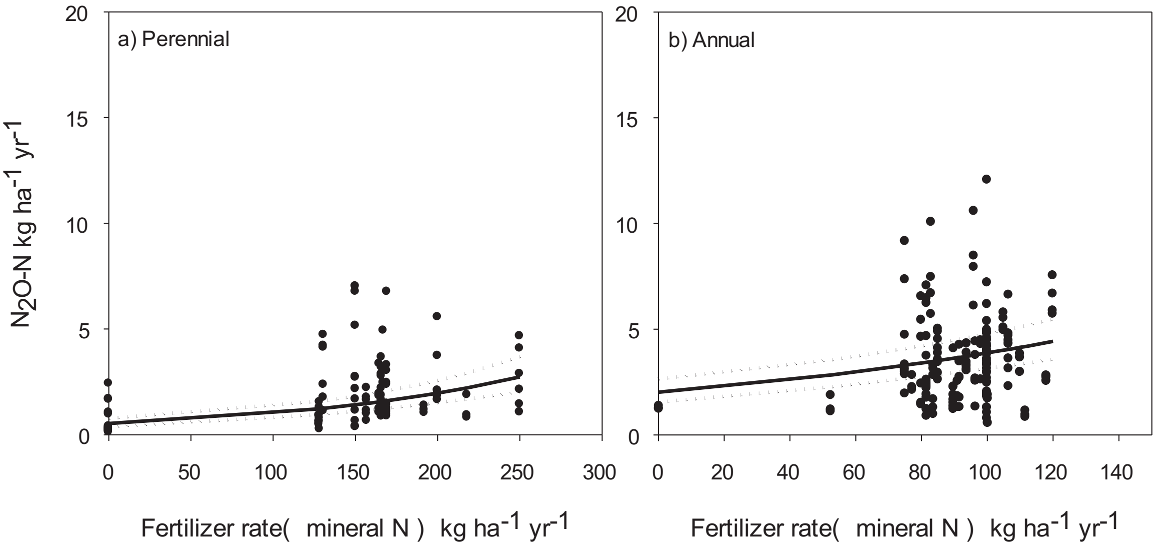

Fig. 3. Measured N_2O emissions and results for model 3 on mineral soils with perennial (a) and annual (b) crops. Dotted lines denote the 95% confidence interval.

Table 4
Comparison of model results for annual N_2O emission rates with typical fertilizer rate examples.

Crop type	Fertilizer type/rate	N_2O-N (kg ha^{-1} yr^{-1}) (95% confidence interval)			
		Model 1	Model 2	Model 3	Model 4
Annual	Mineral/100 kg N	3.7 (2.9–4.6)	3.8 (3.0–4.8)	3.9 (3.1–4.8)	3.8 (3.0–4.8)
Perennial	Mineral/180 kgN	1.5 (1.1–1.9)	1.6 (1.3–2.1)	1.7 (0.9–3.4)	1.7 (1.2–2.2)
Annual	Organic/100 kgN	–	4.3 (3.2–5.7)	–	4.8 (3.6–6.3)
Perennial	Organic/180 kgN	–	1.1 (0.8–1.5)	–	1.4 (0.8–1.6)

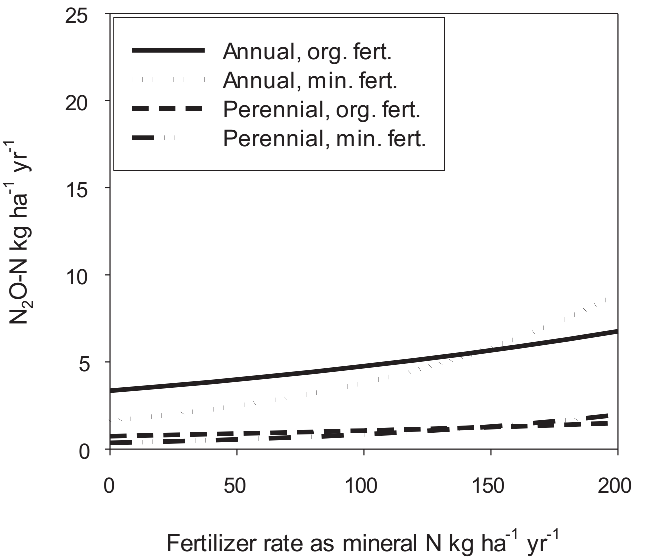

Fig. 4. Model 4 results for perennial and annual crops either with mineral or organic fertilizers.

5. Conclusions

The main finding in this study was that despite the higher fertilizer rate of grass crops the annual emissions of N_2O were lower from grass crops than from annual crops. The long non-vegetated period between harvesting and sowing in boreal conditions with long winter increases the emissions from annual crops. We were able to provide a country-specific method for estimating N_2O fluxes from mineral soils with somewhat more precision than e.g. the IPCC default methodology. However, the data is still scarce and limited to typical cultivation practices and does not allow recommendations for mitigating these emissions other than reducing the fertilizer rate. Data on the effect of practices like cover crops, catch crops, split application of fertilizer or precision farming are still lacking. More abundant data also from less common cultivation systems across the country would enable smaller uncertainties and more detailed calculation methods with numeric estimates of the effects of potential new mitigation measures.

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