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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