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Nitrous oxide emissions from perennial grass cropping systems on a boreal mineral soil

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Agriculture is the main anthropogenic source of nitrous oxide (N_2O). Cultivation of perennial crops is a potential way to reduce N_2O emissions. We quantified multi-year N_2O emissions from two perennial cropping systems, reed canary grass (RCG) and a mixture of timothy and meadow fescue (TIM), on a boreal mineral soil. Mean annual emissions from TIM and RCG were rather similar, 600 mg N_2O m^{-2} yr^{-1} and 670 mg N_2O m^{-2} yr^{-1}, respectively. Compared to the median N_2O emissions from cropping systems in mineral soils in northern Europe (230 mg N_2O m^{-2} yr^{-1}), those in this study (720 mg N_2O m^{-2} yr^{-1}) were higher. The higher annual emissions and the observed decrease in annual emissions in our study with time was likely associated with the use of organic fertilizer during the pre-trial period.

Introduction

Nitrous oxide (N_2O) is an ozone-depleting substance in the stratosphere (Ravishankara *et al*. 2009) and a strong greenhouse gas (GHG) with a global warming potential (GWP) of 265 on a 100-year time horizon (Myhre *et al*. 2013). The concentration of N_2O in the atmosphere has increased since the 1750s, with the present global mean being 328 ppb (WMO 2016). Natural sources of atmospheric N_2O are oceans, fresh water ecosystems and natural terrestrial ecosystems (Ciais *et al*. 2013). The main sinks of N_2O are photolysis and reactions with oxygen radicals in the stratosphere (Ciais *et al*. 2013). Agriculture is the main anthropogenic source of N_2O and responsible for approximately 60% of the total anthropogenic N_2O emissions (Syakila and Kroeze 2011). Other sources include industrial processes and combustion (Ciais *et al*. 2013). Thus, the reduction of agricultural N_2O emissions is important in our attempts at decreasing the global N_2O load to the atmosphere.

Agricultural N_2O emissions include direct and indirect emissions. The direct N_2O emissions originate from fertilized soils and animal manure, whereas indirect emissions derive e.g., from nitrogen leached to the surrounding

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aquatic ecosystems (Syakila and Kroeze 2011). Soil N_2O emissions have been estimated to be 1.8 Tg N $year^{-1}$ (Syakila and Kroeze 2011). In agricultural soils, the main N_2O production processes are microbial denitrification and nitrification (e.g., Wrage *et al*. 2001). Emissions from soils are affected by agricultural practices such as fertilizer and crop management. Also, soil conditions such as temperature, moisture, organic C content and texture (Hénault *et al*. 2012, Tian *et al*. 2015) affect N_2O dynamics. The global demand for food, fodder and fuel is increasing. This could trigger higher N_2O emissions as a result of intensification of agriculture (Reay *et al*. 2012). Therefore, it is important to quantify and characterize N_2O emissions as affected by different cropping systems and agricultural management practices so that proper N_2O mitigation strategies could be adopted.

Nitrous oxide flux patterns are highly variable. Fertilized agricultural soils are generally N_2O sources, but uptake of N_2O is also being reported in many studies (e.g., Neftel *et al*. 2007, Hyvönen *et al*. 2009). Episodic high releases of N_2O associated with fertilization events are typical for agricultural soils (e.g., Flechard *et al*. 2005, Maljanen *et al*. 2007a), soil thawing and freezing (e.g., Wagner-Riddle and Thurtell 1998, Teepe *et al*. 2001, Koponen *et al*. 2004, Maljanen *et al*. 2009), precipitation events (e.g., Maljanen *et al*. 2004, Regina *et al*. 2004, Flechard *et al*. 2005) and ploughing of soil (e.g., Regina *et al*. 2004). Moreover, while our current understanding of N_2O dynamics mostly stems from studies with manual chamber technique with sparse sampling interval, studies employing continuous flux measurement techniques, such as automated chambers and eddy covariance, have reported agricultural N_2O emissions with contrasting diurnal patterns (Maljanen *et al*. 2002, Shurpali *et al*. 2016, Keane *et al*. 2018).

Perennial cropping systems have environmental benefits when compared with annual systems. Perennial systems have a year-round plant cover that reduces the risks for soil erosion and nutrient leaching (Saarijärvi *et al*. 2004). They a have higher potential to capture carbon due to early plant development and therefore, for better utilization of the growing season (Dohleman and Long 2009). They also increase the soil carbon storage (DuPont *et al*. 2010, Kätterer *et al*. 2011). Additionally, perennial systems require less energy inputs as fewer field management operations are carried out and the use of fertilizers and herbicides is lower. The most important perennial grassland species in the boreal region are timothy (*Phleum pratense*) and meadow fescue (*Festuca pratensis* Huds.), which are often cultivated as a mixture (Niskanen and Nieméläinen 2010). They are used as silage for dairy farms and hay and also as a substrate for biogas reactors (Lehtomäki *et al*. 2008). Perennial reed canary grass (RCG, *Phalaris arundinaceae* L.) performs well in boreal climate and can be applied to mitigate carbon losses from drained organic soil (Hyvönen *et al*. 2009, Shurpali *et al*. 2009). RCG is used for fodder and pasture, but also for bioenergy and biofuel production, substrate for biogas reactors, wastewater disposal and pollution abatement (Pasila and Kymäläinen 2000; Lewandowski *et al*. 2003, Powlson *et al*. 2005, Lehtomäki *et al*. 2008, Lakaniemi *et al*. 2010).

The aim of this study was to evaluate the atmospheric importance of N_2O emissions from perennial cropping systems under boreal climatic conditions. We determined N_2O emissions for three years from two different perennial cropping systems on a mineral soil in eastern Finland. Emissions were measured with manual chamber and snow gradient methods from a mixture of timothy and meadow fescue (TIM) and reed canary grass (RCG). Also, bare soil without vegetation (BARE) was included in the study for comparison.

Material and methods

The study site and experimental design

The study site is located in Maaninka (63°09′49′′N, 27°14′3′′E, 89 m above the mean sea level) in eastern Finland with a mean annual air temperature of 3.2°C and a precipitation sum of 612 mm (30 years, reference period 1981–2010; Pirinen *et al*. 2012). It is a 6.3 ha agricultural field which has been cultivated with grass (*Phleum pratense* L.; *Festuca pratensis* Huds), barley (*Hordeum vulgare* L.) or oat

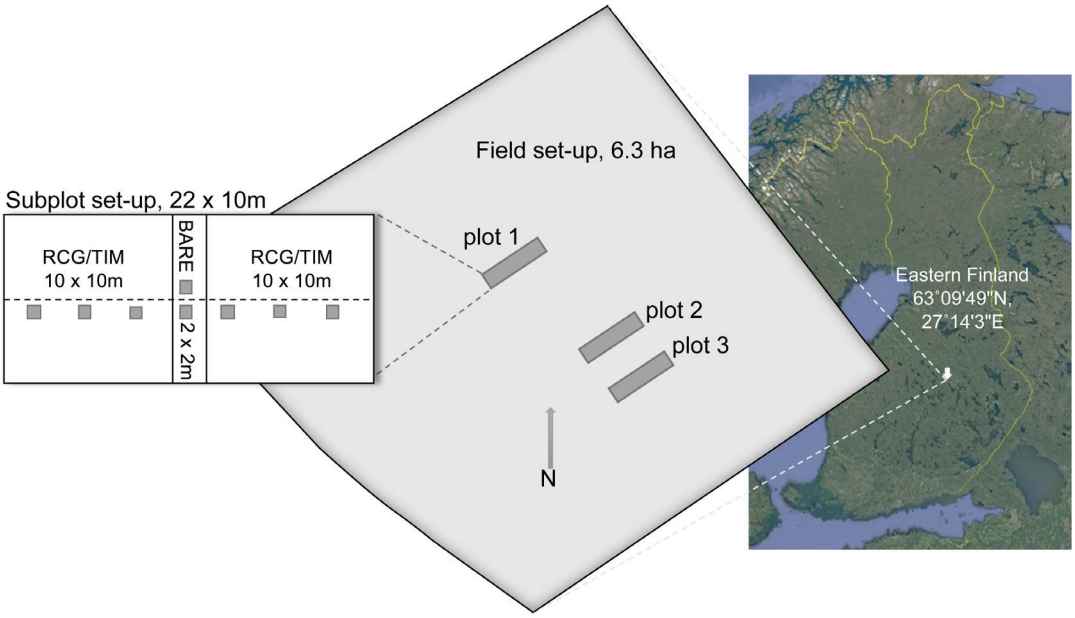

Fig. 1. General location of the study site and the set-up at field and subplot levels. Three plots (grey) were placed in the middle section of the field. The plots were further divided to subplots. On each subplot, one end (10 m × 10 m area) was cultivated with mixture of timothy and meadow fescue (TIM) and another with reed canary grass (RCG). Order of the TIM and RCG varied. Between of the two vegetated parts a 2 m × 2 m area was kept without vegetation (BARE). Grey squares in the subplots mark the location of the collars used for flux measurements. Map data: © 2018 Google.

(*Avena sativa* L.) prior to the current experiment. The soil is classified as a Haplic Cambisol/Regosol (Hypereutric, Siltic) (IUSS Working Group WRB 2007), the topsoil being silt loam based on the U. S. Department of Agriculture (USDA) textural classification system. The mean properties of the top soil (0–18 cm) are as follows: particle density is 2.7 g cm^{-3}, bulk density is 1.1 g cm^{-3}, soil organic matter is 5.2%, total nitrogen is 0.2%, C:N ratio is 15 and pH (H_2O) is 5.8. More information about the study site can be found in Lind *et al*. (2016).

The treatments (TIM, RCG and BARE) were established in June 2009. The experimental design consisted of three plots with three subplots per plot (Fig. 1). They were cultivated with RCG (*Phalaris arundinaceae* L, cv. "Palaton", hereafter RCG), mixture of timothy (*Phleum pratense*, cv. "Tuure") and meadow fescue (*Festuca pratensis Huds*., cv. "Antti", hereafter TIM) or kept without vegetation (hereafter BARE). TIM was established using barley (*Hordeum vulgare*, cv. "Voitto") as a cover crop. Mineral fertilizers (approximately 50/50, NH_3–N and NO_3–N ratio) were applied together with seeds in 2009 and later as a surface application (Table 1). A herbicide (Ariana-S) was applied by the end of July 2009 to control weeds on TIM and RCG. On BARE plots, all vegetation was removed on a weekly basis by handpicking. Bare plots were neither fertilized nor treated with herbicides at any time during the study. Crops were harvested (Table 1) using a plot harvester on the plots (Haldrup 1500 plot harvester, Løgtør, Denmark).

Nitrous oxide emissions

To determine the annual N_2O exchange, season-specific flux measurement methods were applied. During snow-free seasons, N_2O emissions were determined using a dark static chamber method with permanent collars (Nykänen *et al*. 1995). During snow-covered seasons, the snow gradient method (Sommerfeld *et al*. 1993) was used to determine N_2O emissions through the snowpack. In addition, the fluxes were measured before the establishment of treatments with a dark static chamber method

without collars (Maljanen *et al*. 2006) from April to June (5 times) in 2009. According to this method, chambers were inserted 2–5 cm deep in the soil for gas flux measurement and no permanent collar installations were needed. Chambers were removed from the soil after each measurement. After the experimental design was established, the chamber system with permanent collars was used. In its place, aluminium collars (60 cm × 60 cm × 15 cm) with water grooves were permanently installed to ensure gas-tight closure during chamber deployment (Nykänen *et al*. 1995). On each subplot of TIM and RCG, three collars were installed. There were two collars on BARE subplots.

Snow-free season N_2O exchange was measured from June to December in 2009 (32 times), from April to November 2010 (30 times) and from April to September in 2011 (24 times). Measurements were made between 08:00 and 19:00. Extra collars were used with taller plants. Four gas samples were taken from the chamber headspace during the closure time varying from 28–60 min. Longer closure times were used with extra collars. Gas samples were stored in pre-evacuated vials (Labco Exetainer®) and analysed with a gas chromatograph (GC, Agilent 6890N, Agilent Technologies Deutschland, Germany) equipped with an electron capture detector. A gas mixture with known N_2O concentrations (at ppm: 0.33, 0.39, 0.84 and 3) were used for calibration. Nitrous oxide emissions were calculated from the linear concentration change in the chamber headspace with time. After visual inspection of the data, high fluxes with $R^2 > 0.8$ were accepted. Small fluxes (between ±0.2 mg N_2O m^{-2} d^{-1} and ±0.8 mg N_2O m^{-2} d^{-1} depending on the volume and closure time) were accepted regardless of the R^2 value. With these criteria, 7% of the data were rejected.

Snow-covered season N_2O exchange was measured from February to April during the winter 2008–2009 (5 times), from November to April in the winter 2009–2010 (16 times) and in the winter 2010–2011 (18 times). In a pilot campaign during the winter 2008–2009, the sampling was done along a transect on the field at a 10- to 29-day interval. The objective of these measurements was to gather background information on the N_2O source strength of the ecosystem prior to initiating the investigation with various treatments. During the 2009–2010 and 2010–2011 winters, the gas sampling was done from the subplots approximately at a weekly interval. Gas samples were collected between 09:00 and 20:00 using a metal probe (length 0.5 m or 1.2 m, ∅ 2 mm). Samples were taken at 10-cm intervals from the top of the snow pack down to the soil surface. The gas samples were stored and analysed as described above. The flux calculation was based on the N_2O concentration gradient and diffusion rate of N_2O in the snowpack (diffusion coefficient of 0.14 cm^2 s^{-1}, Sommerfeld *et al*. 1993). After visual inspection of the data, fluxes were accepted when the gas concentration change with depth was considered linear ($R^2 > 0.7$). Small fluxes (±0.1 mg N_2O m^{-2} d^{-1}) were accepted regardless of the R^2 values. With these criteria, 7% of the N_2O data was rejected. Snow samples were col-

Table 1. Fertilization rates (kg ha^{-1}) of nitrogen (N), phosphorus (P) and potassium (K) together with the yields (kg DW ha^{-1}) for mixture of timothy and meadow fescue (TIM) and reed canary grass (RCG). TIM was harvested and fertilized twice in 2010 and 2011 and the yields of each harvest are in brackets.

	Year	Fertilization date	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Harvesting date	Yield (kg DW ha^{-1})
TIM	2009	9 June	60	30	45	21 Aug.	6400
	2010	21 May, 30 Jun.	100, 100	15, 0	25, 35	22 Jun., 23 Aug.	13 000 (7200, 5700)
	2011	27 May, 7 Jul.	100, 100	15, 0	25, 35	22 Jun., 5 Sept.	14 000 (7400, 6400)
RCG	2009	9 Jun.	60	30	45		
	2010	21 May	80	10	20		
	2011	27 May	80	12	20	22 Apr.	7300
	2012					9 May	5700

lected from three locations per treatment using a PVC cylinder (∅ 9 cm) for porosity measurements. The snow porosity was calculated using the density of pure ice (0.92 g cm^{-3}). For annual emission values, the gaps in the data were filled using linear interpolation between data points and then adding the measured and interpolated daily values.

Supporting measurements

Weather variables

The weather station installed at the site measured the air temperature (TA, model: HMP45C, Vaisala Inc) and rainfall at about 1 m height (model: 52203, R.M. Young Company) at 30-minute intervals. Data collection started on 14 August 2009. Missing 30-minute values in the data were filled using linear interpolation. Longer gaps were filled using data from the Maaninka weather station, located about 6 km south-east of the site and operated by the Finnish Meteorological Institute (FMI).

Soil temperatures (TS, sensor: 109, Campbell Scientific Inc., UK and datalogger: CR200, Campbell Scientific Inc.) were measured at 5 cm depth. Measurements on TIM started in June 2009. Alternative temperature loggers (model: DS1921G, Maxim Integrated Products, Inc. USA) were used from June to October 2011. For RCG, soil temperature data were recorded from August 2009 until end of 2011 (sensor: 109, Campbell Scientific Inc., UK and datalogger: CR3000, Campbell Scientific Inc.). For BARE, soil temperature was measured with ibuttons® (model: DS1921G, Maxim Integrated Products, Inc. USA) from July 2009 until the end of 2011. Volumetric water content (VWC) was measured concurrently with the flux measurements from 0–7 cm depth with a moisture meter (HH2 equipped with ThetaProbe ML2x: Delta-T Devices Ltd.) adjacent to the flux measurement point.

Soil frost development on TIM and RCG subplots (n = 3) was determined using tubes filled with methylene blue solution (Gandahl 1957). Snow depth was measured manually once a week on all subplots (n = 3).

Soil N_2O and inorganic nitrogen

The N_2O concentration in the soil air at 5 cm, 20 cm and 30 cm depths was determined using PVC gas collectors (∅ 1.4 cm, length 50 cm, perforated with holes (∅ 3 mm), Kammann *et al*. 2001) from September 2009 until September 2011 from all treatments. Gas samples were collected twice a month. They were stored for the analysis of N_2O concentrations as described earlier.

Soil samples (n = 3) for the analysis of ammonium (NH_4^+) and nitrate (NO_3^-) concentrations in the soil profile were collected from 0–10 cm (top soil) and 10–25 cm depths using a stainless-steel corer (length 25 cm, ∅ 7 cm) from July to October in 2009 (5 times) and from April to November 2010 (16 times). Soil samples were stored at 4°C before sieving and the extractions for ammonium and nitrate were done within few days. Ammonium was extracted until June 2010 with 2 M KCl (~30 g soil fresh weight (FW), 50 ml 2 M KCl) and afterwards with 1 M KCl for two hours using a shaker (175 rpm). The extracts were stored at –20°C and analysed colorimetrically (Fawcett and Scott 1960) with spectrophotometer (model: Ultrospec 3000, Biochrom, UK). Nitrate was extracted with Milli-Q water (~30 g soil FW, 50 ml Milli-Q water). The extracts were stored at –20°C and analysed with an ion chromatograph (model: DX 120, Dionex Corporation, USA). Soil water content was measured by drying samples for 24 hours at 105°C.

Statistical methods

The Kolmogorov-Smirnov test was used to analyse the normal distribution of the data. As the N_2O data were not normally distributed, the Spearman's rank correlation was used to test the correlation between N_2O flux and relevant environmental variables. Collected data were segregated into the summer period (June–September 2009, May–September 2010 and May–September 2011) and the winter period (November 2009–April 2010 and November 2010–April 2011) prior to data analysis. During the summer time, the tested variables were TA, TS, VWC,

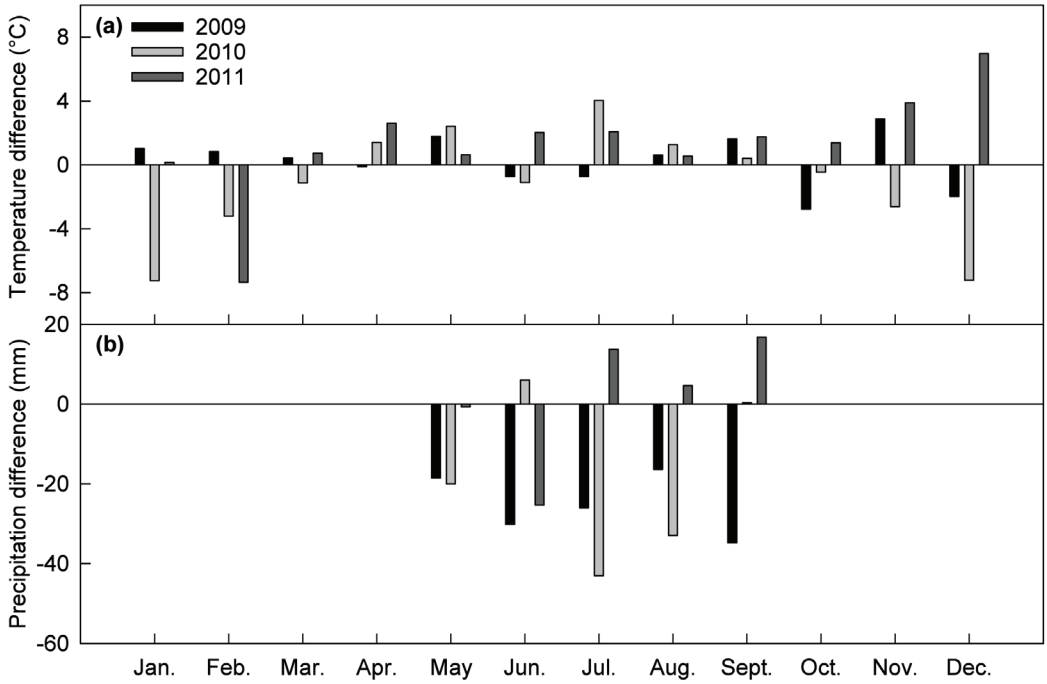

Fig. 2. The (**a**) monthly mean air temperature and (**b**) precipitation anomalies in 2009, 2010 and 2011 relative to the 30-year means. Negative values indicate lower temperature/less precipitation and positive values higher temperature/more precipitation.

N_2O concentration (5 cm, 20 cm and 30 cm depths) in soil and plant heights. During the winter time, tested variables were TA, snow temperature 2 cm above the ground, TS, snow depth, frost depth and N_2O concentration (5 cm, 20 cm and 30 cm depths) in soil. The correlation was considered meaningful when the coefficient was higher than 0.6 and the correlation was statistically significant ($p < 0.05$). All analyses were conducted using IBM SPSS Statistics ver. 21.

Results

Weather conditions

The mean annual air temperature at the study site was 3.4°C, 2.0°C and 4.4°C in 2009, 2010 and 2011, respectively. In general, the summers were warmer and winters were colder compared to the 30-year averages (Pirinen *et al*. 2012). The temperature deviation (mean ± SD) from the long-term mean was 1.1°C ± 1.4°C during May–September (summer), while it was –0.6°C ± 3.6°C during October–April (winter) (Fig. 2a). Annual precipitation in 2009, 2010 and 2011 was 420 mm, 520 mm and 670 mm, respectively. During May–September, the precipitation was received as rain. On an average (mean ± SD), these months were drier (–14 mm ± 19 mm) than the long-term mean seasonal sum (Fig. 2b). There were wetter months in 2011, when July, August and September received on average 12 mm more rainfall than the 30-year mean.

The soil temperature at the 5 cm depth had a clear seasonal pattern with the maximum during the summer and close to zero during winter time (Figs. 3a, 4a, 5a). Summer peaks observed in July of each year ranged from 19°C in RCG in 2011 to 24°C in TIM and BARE in 2010. The winter minima ranged from –4.7°C in the winter 2009–2010 (TIM) to 0°C during the following winter (TIM).

Snow depths were similar between the treatments. The snow depth reached 40 cm in the winter 2008–2009, 60 cm in the winter 2009–2010 and 80 cm in the winter 2010–2011 (Fig. 5a). On the vegetated surfaces, there was

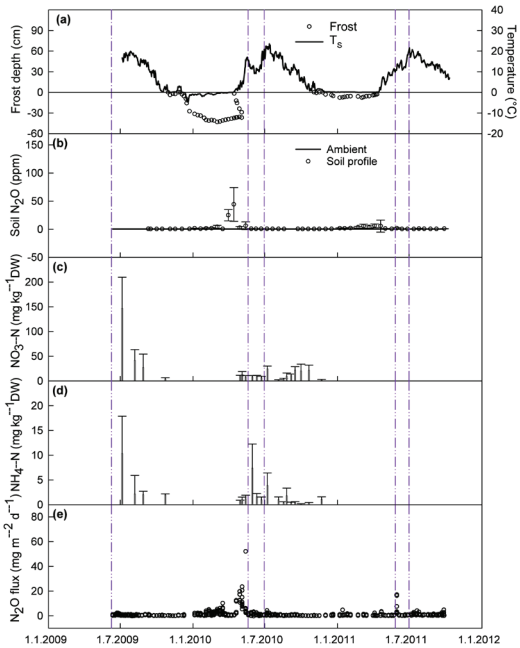

Fig. 3. Nitrous oxide dynamics on mixture of timothy and meadow fescue (TIM). (**a**) Soil temperature at 5 cm depth (TS) from Jul. 2009 until Oct. 2011 together with seasonal frost (black circle) during the winters 2009–2010 and 2010–2011, (**b**) N_2O concentration (ppm) with standard deviation in the soil profile (black circle) and in the atmosphere (black line) from Jun. 2009 to Sep. 2011, (**c**) topsoil nitrate concentration with standard deviation from Jul. to Oct. 2009 and from Apr. to Nov. 2010, (**d**) topsoil ammonium concentration with standard deviation from Jul. to Oct. 2009 and from Apr. to Nov. 2010 and (**e**) nitrous oxide emissions from Jun. 2009 to Sep. 2011. The vertical lines show the timing of the fertilization (once in 2009, twice in 2010 and 2011).

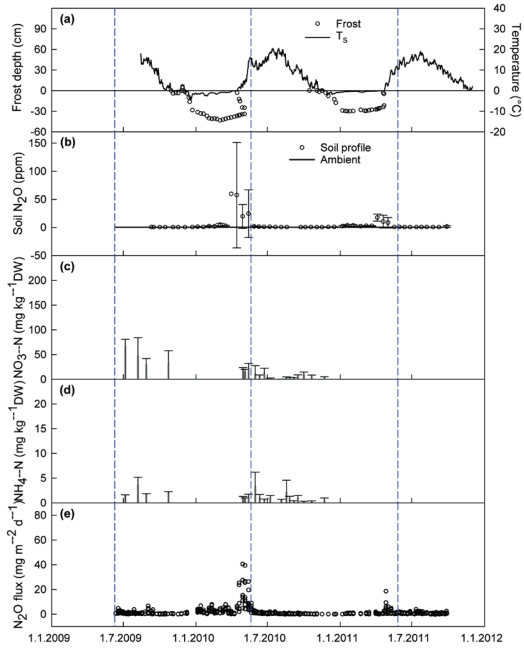

Fig. 4. Nitrous oxide dynamics on reed canary grass (RCG). (**a**) Seasonal frost depth (black circle) during winters 2009–2010 and 2010–2011 together with daily soil temperature at 5 cm depth (TS, black line) from Aug. 2009 until Oct. 2011, (**b**) N_2O concentration in the soil profile with standard deviation (black circle) and in the atmosphere (black line) from Jun. 2009 to Sep. 2011, (**c**) topsoil nitrate and (**d**) ammonium concentration with standard deviation from Jul. to Oct. 2009 and from Apr. to Nov. 2010 and (**e**) nitrous oxide emissions from Jun. 2009 to Sep. 2011. The vertical lines show the timing of the fertilization (once per season).

Table 2. Annual N_2O emission (mg N_2O m^{-2} yr^{-1}) on mixture of timothy and meadow fescue (TIM), reed canary grass (RCG) and bare soil without vegetation (BARE) with standard deviations. Also emissions factor (EF, %) on TIM and RCG are shown. EF is the ratio of emitted N_2O–N (kg N ha^{-1} yr^{-1}) to applied fertilizer N (kg N ha^{-1} yr^{-1}).

	TIM		RCG		BARE
	N_2O (mg N_2O m^{-2} yr^{-1})	EF (%)	N_2O (mg N_2O m^{-2} yr^{-1})	EF (%)	N_2O (mg N_2O m^{-2} yr^{-1})
2009	860 ± 10	9.1	920 ± 10	9.8	880 ± 24
2010	630 ± 140	2.0	800 ± 240	6.4	860 ± 450
2011	320 ± 146	1.0	300 ± 90	2.4	570 ± 250

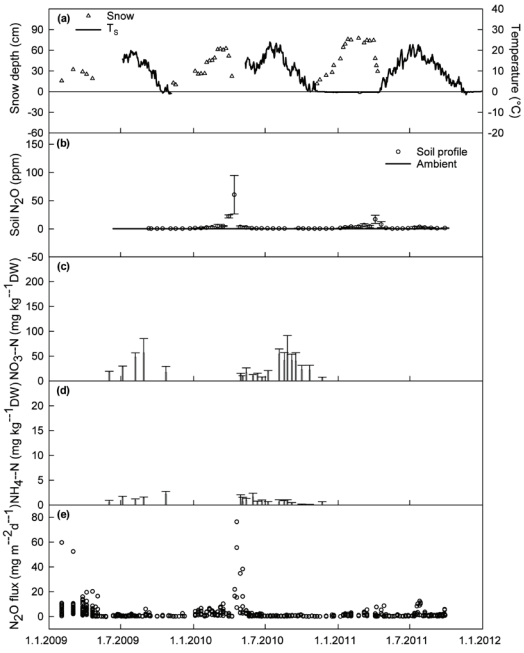

Fig. 5. Nitrous oxide dynamics on bare soil without vegetation (BARE). (**a**) Snow depth (black triangle) during winters 2009–2010 and 2010–2011 together with the daily soil temperature at 5 cm depth from Jul. 2009 until Oct. 2011, (**b**) N_2O concentration in the soil profile (black circle) with standard deviation and in the atmosphere (black line) from Jun. 2009 to Sep. 2011, (**c**) topsoil nitrate concentration with standard deviation from Jul. to Oct. 2009 and from Apr. to Nov. 2010, (**d**) topsoil ammonium concentration with standard deviation from Jul. to Oct. 2009 and from Apr. to Nov. 2010 and (**e**) nitrous oxide emissions from Feb. 2009 to Sep. 2011.

seasonal frost during the latter two winters (Figs. 3a, 4a). On TIM and RCG, the frost depth reached 43 cm during the winter 2009–2010. In the winter 2010–2011, the seasonal frost did not exceed 10 cm depth in TIM, whereas the maximum frost depth in RCG was 30 cm.

N_2O concentrations and inorganic nitrogen content in the soil profile

Nitrous oxide concentrations in the soil profile increased around the time of frost and snow thaw in the spring during both 2010 (up to 60 ppm) and 2011 (up to 17 ppm) across the treatments (Figs. 3b, 4b, 5b). Outside the spring thaw period, N_2O concentrations in the soil were close to the ambient levels. In vegetated treatments, the topsoil nitrate concentration peaked in July 2009 and decreased thereafter (Figs. 3c, 4c). In 2010, the mean nitrate concentrations were 11 mg NO_3–N kg^{-1} DW and 8 mg NO_3–N kg^{-1} DW in TIM and RCG, respectively. For BARE, nitrate concentrations were similar between the two study seasons, with mean concentrations of 41 NO_3–N kg^{-1} DW and 23 mg NO_3–N kg^{-1} DW (Fig. 5c) in 2009 and 2010, respectively. Nitrate concentrations were generally higher in topsoil than deeper in the soil (Appendix Table A1).

The topsoil ammonium concentration peaked after the fertilizer events in TIM (Fig. 3d). For RCG, fertilisation related peaks were not clear (Fig. 4d). The mean ammonium concentrations in the topsoil in 2009 were 3.7 mg NH_4–N kg^{-1}, 3.4 mg NH_4–N kg^{-1} and 1.4 mg NH_4–N kg^{-1} DW in TIM, RCG and BARE, respectively. During the second season, the averages were 1.5 NH_4–N kg^{-1}, 1.1 NH_4–N kg^{-1} and 0.7 NH_4–N kg^{-1} DW in TIM, RCG and BARE, respectively. Additional information on soil ammonium concentrations are shown in Appendix Table A2.

Nitrous oxide dynamics

The measured N_2O fluxes and environmental variables were not correlated ($r_s < 0.6$, $p > 0.05$). Nitrous oxide emissions ranged from being close to 0–52 mg N_2O m^{-2} d^{-1}, 40 mg N_2O m^{-2} d^{-1} and 76 mg N_2O m^{-2} d^{-1} in TIM, RCG and BARE, respectively (Figs. 3e, 4e, 5e). High N_2O emissions were measured during the February–May period in 2009 (BARE), during spring thaw in 2010 (all treatments) and in 2011 (RCG). Emission peaks after the fertilizer applications were not observed, except for the first fertilization event in 2011 in TIM.

Annual N_2O emissions ranged from 920 mg N_2O m^{-2} yr^{-1} in 2009 to 300 mg N_2O m^{-2} yr^{-1} in 2011 (Table 2). These emissions decreased by 63% in TIM, by 67% in RCG and by 35% in BARE from 2009 to 2011. The January to April period in 2009 accounted for 84% of the annual emission in all treatments. The main emissions were observed in April and May in 2010. They accounted for

59% of the annual emissions. In 2011, the monthly differences were less pronounced. The cumulative N_2O emissions were 1.8 g N_2O m^{-2}, 2.0 g N_2O m^{-2} and 2.3 g N_2O m^{-2} in TIM, RCG and BARE, respectively, during the three-year study period.

Since both TIM and RCG are managed grasslands, we determined emission factors (EF % as a ratio of annual N_2O–N emitted per kg of applied N) for the study years. These emission factors ranged from 9.8% in RCG in 2009 to 1.0% in TIM in 2011 (Table 2).

Discussion

Nitrous oxide dynamics

Annual N_2O emissions were similar from TIM and RCG (Table 2). BARE without fertilization had similar annual emissions as the fertilized TIM and RCG, indicating the importance of plant nitrogen uptake in controlling N_2O emissions. The interannual variability in the emissions was caused mainly by the emissions during the January to May period. Nearly 86% of the annual emissions (750 mg N_2O m^{-2}) occurred in the January–April period in 2009 and 59% (450 mg N_2O m^{-2}) during the April–May period in 2010. Land-use history and climatic/soil conditions had likely an impact on the annual emissions at the study site. As indicated earlier, a pilot N_2O campaign was conducted at the study site during the 2008 growing season prior to this study in 2009–2011. The site was then fertilized with dairy cow slurry (40 tons ha^{-1} containing 120 kg N ha^{-1}, 19 kg P ha^{-1} and 112 kg K ha^{-1}) in late April 2008 and the RCG crop was sown by mid-June in 2008. However, the seed germination failed, and the subsequent plant growth was poor. To destroy the remaining plant growth, glyphosate, a systemic herbicide, was applied in September 2008. Following this, the field was ploughed in November 2008 and left to overwinter as a bare soil. It is possible that the addition of high amount of organic N fertilization followed by poor plant growth, glyphosate application (Saarijärvi *et al*. 2004) and ploughing of the soil (Regina *et al*. 2004) all contributed to the build-up of a high soil N content leading to increased N mineralization and N_2O emissions in 2009, the first year of the experiment. The N addition in 2008 could also have some impact on the N_2O dynamics in later years (Saarijärvi and Virkajärvi 2009).

Although there were no short-term correlations between climatic variables and N_2O emissions, there were some climate and soil related differences on an annual basis that could have impacted the emissions during the January to May periods. As mentioned earlier, the winter 2008–2009 contributed most (86%) of the annual emissions in 2009. The importance of winter emissions in the annual N_2O emissions from boreal agricultural soils has been observed in other studies as well (e.g., Maljanen *et al*. 2009). Nitrous oxide production in the soil continues in winter even when the air temperature is far below zero. The snow cover keeps soil temperatures above air temperatures and thus acts as an insulating agent, favoring winter emissions (e.g., Maljanen *et al*. 2009). There is evidence from the laboratory studies that in boreal agricultural soil, N_2O emissions can increase when the soil temperature is around 0°C (Koponen *et al*. 2004). However, whether the N_2O produced in the soil is emitted to the atmosphere depends on e.g., the soil water content and frost which affect the gas diffusivity (Smith *et al*. 1998, van Bochove *et al*. 2001). Prior to this study, the soil was ploughed in the autumn of 2008, leaving the soil surface porous and uneven. Although we do not have soil frost measurements from the winter 2008–2009, there were perhaps no gas impermeable ice layers in the soil preventing the escape of the produced N_2O. This may explain the lack of N_2O emission peak during the spring thaw in 2009 as N_2O did not build-up in the soil in contrast to the winter 2009–2010. In the winter 2009–2010, the soil was levelled and soil frost (Figs. 3a and 4a) was observed together with N_2O build-up in the soil (Figs. 3b, 4b and 5b). The winter emissions in 2009–2010 were lower than in the winter 2008–2009 but they increased in April and May, at the time of soil and snow thaw, across the treatments. In the winter 2010–2011, frost depth in TIM was low and not consistent compared to RCG. However, the annual emissions were similar between the two treatments. The soil N_2O concentration increased

in the springtime in both treatments but not as clearly as during the spring in 2010, indicating that there was less N_2O accumulation in the soil than during the winter 2009–2010. These results indicate that both land-use history and climate/soil conditions affected the winter/spring time emissions and finally the annual emissions.

Owing to the use of manual chamber methods to monitor N_2O dynamics at our site, it is likely that the N fertilizer-induced N_2O emissions peaks were not totally covered. However, an N_2O emission peak from the RCG crop growing on the main field of the study site was captured with the eddy covariance (EC) method in 2011 (Rannik *et al*. 2015; Shurpali *et al*. 2016). The EC measured a N_2O peak lasting three days, which was observed a day after the fertilizers were applied, while the chamber measurements were carried out four days after the fertilizer was applied. According to the EC results, approximately 55 mg N_2O m^{-2} were emitted soon after the fertilizer application. Based on a single season EC estimate of the peak emissions, it is difficult to estimate the duration and magnitude of the possible fertilizer-induced N_2O peaks in other years. Therefore, the annual data reported here do not account for the possible missed fertilizer peaks.

Comparison with nitrous oxide emissions from agricultural soils in northern Europe

To put the nitrous oxide emissions from the present study into perspective, we compiled N_2O emission data from agricultural soils in northern Europe (Appendix Table A3). We used publications that reported annual N_2O values based on year-round measurements. Thus, we found a total of 68 sites, including the present study, where annual N_2O emissions have been estimated. The sites are located between 53°N and 67°N, and the cropping systems were harvested (thus excluding mulching or grazing studies) and fertilizer applied (unless the site was fallow/bare). Most of these studies were carried out on mineral soils (68%), 54% had annual crops, 32% had perennial crops and 13% had fallows/bare soils. Annual crops were barley (*Hordeum vulgare* L.), rye (*Secale cereale*), rapeseed (*Brassica napus*), oilseed (*Brassica rapa*), wheat (*Triticum aestivum*), oat (*Avena sativa* L.), whole crop silage, corn (*Zea mays*), pea and potato (*Solanum tuberosum*). Perennial crops were reed canary grass (*Phalaris arundinaceae* L.), buffalo grass (*Anthoxanthum odoratum* L.), ryegrass (*Lolium perenne* L.) and other grasses and their mixtures (e.g., *Phleum pratense* L., *Festuca pratensis* Huds, *Trifolium pretense*, *Trifolium hybridium*). Fallows/bare soils were kept free of vegetation either by hand-picking, by spraying herbicides or by ploughing.

The mean annual N_2O emissions from TIM (600 mg N_2O m^{-2} yr^{-1}), RCG (670 mg N_2O m^{-2} yr^{-1}) and BARE (770 mg N_2O m^{-2} yr^{-1}) treatments in this study were within the range of the published N_2O values (Appendix Table A3). The range of the N_2O emissions in the compiled data varied from 10 mg N_2O m^{-2} yr^{-1} to 4000 mg N_2O m^{-2} yr^{-1}. The lowest and highest emissions were reported for Finnish drained organic soils without permanent vegetation. An active peat extraction site in eastern Finland had the lowest annual value (Hyvönen *et al*. 2009) and a fallow site in southern Finland had the highest annual value (Regina *et al*. 2004). Prior to fallowing this high emission site, it was cultivated with potato and had annual emissions of 1600 mg N_2O m^{-2} (Appendix Table A3, Regina *et al*. 2004). The variation in the N_2O emissions in organic soils has been linked to soil C/N ratios. The N_2O emission potential from organic soils increases with a decreasing C/N ratio. The high emitting organic soils have C/N ratios lower than 25 (Klemedtsson *et al*. 2005; Maljanen *et al*. 2007b). The site with the lowest N_2O emissions (Hyvönen *et al*. 2009) had the highest C/N ratio (42) among the sites. However, it has to be noted that there are other factors, such as P availability, in addition to the C/N ratio, which can affect the N_2O emissions from organic soils (Liimatainen *et al*. 2014, Liimatainen *et al*. 2018).

The compiled data from northern Europe was grouped based on crop (annual or perennial) and soil types (organic or mineral). The overall range of the N_2O emissions was high with annual crops cultivated on organic soils and low with perennial crops on mineral soils (Fig. 6). Annual crops

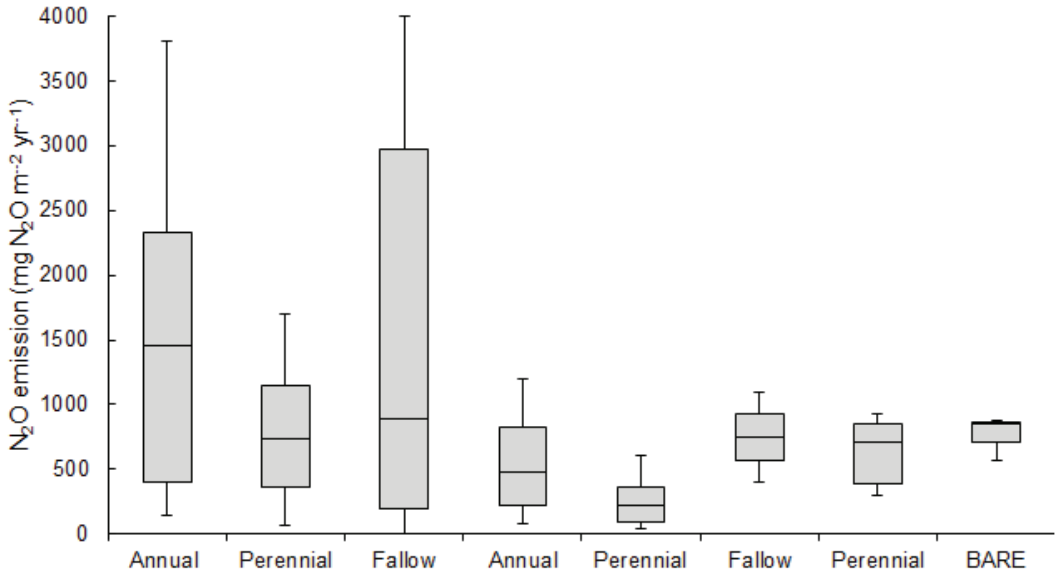

Fig. 6. Boxplot of nitrous oxide emissions (mg N_2O m^{-2} yr^{-1}) from organic and mineral soil for annual and perennial cropping systems and also for fallow/bare soils in northern Europe. Annual emission data from this study for perennial cropping systems (mixture of timothy and meadow fescue and also reed canary grass) and bare soil without vegetation (BARE) are also shown. Data are from Appendix Table A3.

on organic soils had the highest median N_2O emissions (1500 mg N_2O m^{-2} yr^{-1}, n = 10) and perennial crops on mineral soils had the lowest ones (230 mg N_2O m^{-2} yr^{-1}, n = 10). In general, the median annual N_2O emissions from perennial crops in this study (RCG and TIM) were higher than those from perennial crops on mineral soils in northern Europe (Table 2, Fig. 6). As discussed earlier, the high emissions from these perennial crops cultivated at our site, especially in the earlier years, could result from the land-use history of the site prior to our experiment.

Emission factors (EFs) defined as the ratio (%) of N_2O–N emitted per kg of applied N ranged from 0.14% to 25% in agricultural soils in northern Europe (Appendix Table A3). The highest EF was reported for spring barley on a drained organic soil in Finland (Regina *et al*. 2004). There, the average N_2O emission was 15 kg N_2O–N ha^{-1} yr^{-1} with a fertilization rate of 60 kg N ha^{-1}. The lowest EF was from a grassland site on a mineral soil in Denmark (Flechard *et al*. 2007), with an average emission of 0.29 kg N_2O–N ha^{-1} yr^{-1} and fertilization rate of 200 kg N ha^{-1}. The EF values from this study (Table 2) were within the range of those from the cropping systems in northern Europe (Appendix Table A3). In each of the studied years, the EF was lower from TIM than from RCG, indicating that timothy and meadow fescue-based perennial grassland, despite receiving more N than RCG, was able to use the applied N more effectively than RCG.

Conclusions

Sound agricultural policies are required to limit the N_2O load to atmosphere from fertilized agricultural soils and mitigate climate change. Here, two perennial cropping systems, timothy-meadow fescue mixture (TIM) and reed canary grass (RCG), and also a soil without vegetation, were studied on a boreal mineral soil to determine their N_2O exchange and its controlling factors. The annual N_2O emissions in this study ranged from 300–920 mg N_2O m^{-2} yr^{-1} across the treatments. It is possible that the higher annual N_2O emissions in 2009 and 2010 were due to the excess of nitrogen from the organic fertilizer left over in the soil due to poor plant growth and also glyphosate application in 2008. The winter

months were important sources of N_2O. This highlights the need for continuous annual measurements for an accurate assessment of annual N_2O exchange. To put the reported annual values in perspective, N_2O emissions from literature for different cropping systems and fallows in northern Europe were compiled. In northern Europe, the range of the annual N_2O emissions varied from 10–4000 mg N_2O m^{-2} yr^{-1}. Our values reported here are within that range. When this compiled data were grouped based on the vegetation and soil type, the median value of N_2O emissions was the lowest in the perennial cropping systems on mineral soil followed by that of annual systems on mineral soils. This shows that the perennial cropping systems have a higher potential to mitigate N_2O emissions from agricultural soils than annual systems.

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Appendix

Table A1. The mean nitrate (NO_3^-) concentration (mg NO_3–N kg^{-1} DW) at 0–10 cm and 10–25 cm depths on mixture of timothy and meadow fescue mixture (TIM), reed canary grass (RCG) and bare soil without vegetation (BARE) for sampling occasions in 2009 and 2010. Dashed lines are undetermined data.

		TIM		RCG		BARE	
		0–10 cm	10–25 cm	0–10 cm	10–25 cm	0–10 cm	10–25 cm
2009	22 May	—	—	—	—	17	—
	2 Jun.	—	—	—	—	17	14
	6 Jul.	150	30	66	27	28	20
	28 Jul.	—	—	104	—	57	—
	7 Aug.	41	13	46	30	48	45
	28 Aug.	27	26	29	18	57	24
	23 Oct.	3.8	13	31	47	17	38
2010	23 Apr.	—	10	8.1	—	3.2	—
	30 Apr.	11	10	21	7.4	13	13
	5 May	13	8.8	14	13	8.6	11
	14 May	7.5	3.1	21	9.5	17	10
	31 May	8.0	5.3	11	3.3	9.6	12
	11 Jun.	8.2	4.5	6.1	6.3	15	21
	23 Jun.	6.4	5.9	13	7.2	6.4	17
	8 Jul.	24	1.6	2.6	3.5	19	21
	5 Aug.	2.3	5.4	0.4	0.7	54	19
	18 Aug.	2.9	5.9	3.1	1.9	41	25
	26 Aug.	9.6	5.4	2.7	1.5	53	29
	6 Sept.	11	6.8	2.7	3.3	41	30
	16 Sept.	22	7.5	5.3	4.6	40	32
	1 Oct.	20	15	8.5	9.3	22	31
	21 Oct.	22	4.3	5.0	4.7	22	35
	22 Nov.	2.5	—	4.4	2.1	6.4	22

Table A2. The mean ammonium (NH_4^+) concentration (mg NO_3–N kg^{-1} DW) at 0–10 cm and 10–25 cm depths on timothy and meadow fescue mixture (TIM), reed canary grass (RCG) and bare soil without vegetation (BARE) for sampling occasions in 2009 and 2010. Dashed lines are undetermined data.

		TIM		RCG		BARE	
		0–10 cm	10–25 cm	0–10 cm	10–25 cm	0–10 cm	10–25 cm
2009	22 May	—	—	—	—	0.7	—
	2 Jun.	—	—	—	—	0.6	0.4
	6 Jul.	10	1.6	1.4	1.6	1.5	1.7
	28 Jul.	1.8	—	8.2	—	1.2	—
	7 Aug.	2.2	0.9	3.6	0.5	0.9	0.5
	28 Aug.	2.0	1.5	1.7	1.5	1.4	1.3
	23 Oct.	2.0	1.9	2.1	2.5	2.2	1.7
2010	23 Apr.	2.0	—	2.9	—	1.8	—
	30 Apr.	0.6	0.6	1.0	2.2	1.2	0.4
	5 May	1.1	0.5	0.7	0.4	0.6	0.0
	14 May	1.2	0.4	1.2	0.6	0.9	0.4
	31 May	7.4	0.8	3.3	1.3	1.6	1.8
	11 Jun.	1.6	0.7	1.1	0.5	0.7	0.5
	23 Jun.	1.0	0.3	0.6	0.6	0.6	0.6
	8 Jul.	3.9	0.5	1.2	0.8	0.5	1.1
	5 Aug.	1.0	0.4	0.5	0.8	0.6	0.1
	18 Aug.	0.4	0.6	2.2	0.5	0.6	0.4
	26 Aug.	1.8	0.9	0.8	0.5	0.9	0.3
	6 Sept.	0.4	0.1	0.4	0.2	0.3	0.4
	16 Sept.	0.4	0.4	1.0	0.4	0.0	—
	1 Oct.	0.2	0.1	0.2	0.2	0.2	0.1
	21 Oct.	0.3	0.3	0.3	0.2	0.1	0.2
	22 Nov.	1.1	1.2	0.6	0.3	0.5	0.5

Table A3. Nitrous oxide emissions (mg N_2O m^{-2} yr^{-1}) from agricultural soils in northern Europe. Measurement years, soil type (organic soil (O), mineral soil (M), C:N ratio, crop type (barley (B), spring barley (SB), reed canary grass (RCG), bare soil without vegetation (BARE), winter rye (WR), spring oilseed rape (SOR), SW (spring wheat), buffalo grass (BF), ryegrass (RG), grass clover (GC), oat (O), potato (P), winter oilseed rape (WOSR), whole crop silage (WCS)), crop cycle (annual (A), perennial (P)), average nitrogen fertilizer amount (kg N ha^{-1} yr^{-1}) and emissions factor (%) are given. More details of the studies can be found from the references within. Dashed lines are unavailable data.

Area	Period	Soil type	C:N	Crop	Crop cycle	Fertilizer (N)	N_2O emission	EF (%)	Reference
FI	2001–2002	O	21	fallow	—	0	4000	—	Regina *et al.* 2004
DK	2014	O	24	P+SB	A	120	3800	20	Kandel *et al.* 2018
FI	2000	O	—	bare	—	0	3600	—	Maljanen *et al.* 2004
DE	2012–2013	O	12	WCS	A	150	2900	12	Poyda *et al.* 2016
FI	2000–2002	O	21	SB	A	60	2400	25	Regina *et al.* 2004
FI	2001–2002	O	18	SB	A	60	2100	22	Regina *et al.* 2004
FI	1997	O	16	grass	P	100	1700	11	Maljanen *et al.* 2003
FI	2000	O	21	P	A	100	1600	10	Regina *et al.* 2004
FI	2000	O	31	B	P	100	1300	8.5	Maljanen *et al.* 2004
FI	1996–1997	O	16	B	A	57	1300	15	Maljanen *et al.* 2003
FI	—	M	—	B	A	85	1200	9.3	Regina *et al.* 2013
FI	2000–2002	O	21	grass	P	130	1200	5.7	Regina *et al.* 2004
FI	2008–2009	M	20	SB	A	75	1200	11	Sheehy *et al.* 2013
FI	2000–2002	M	13	fallow	—	0	1100	—	Syväsalo *et al.* 2004
FI	1996	O	16	bare	—	0	1100	—	Maljanen *et al.* 2003
FI	—	M	—	B	A	110	1000	6.1	Regina *et al.* 2013
FI	2006	O	13	grass	P	70	1000	9.4	Maljanen *et al.* 2009
FI	2009	M	15	SW	A	110	1000	6.1	Sheehy *et al.* 2013
FI	2000–2002	M	15	SB	A	100	880	5.6	Syväsalo *et al.* 2004
FI	2002	M	16	B	A	160	870	3.4	Petersen *et al.* 2006; Regina *et al.* 2013
FI	1991–1992	O	19	grass	P	—	850	—	Nykänen *et al.* 1995
FI	—	M	—	rapeseed	A	110	830	5.0	Regina *et al.* 2013
FI	2008	M	15	SOR	A	110	830	5.0	Sheehy *et al.* 2013
DE	1993	M	9.7	corn (row)	A	79	830	6.7	Mogge *et al.* 1999
FI	2009–2011	M	15	BARE	—	0	770	—	**Present study**
FI	2001–2002	O	18	fallow	—	0	690	—	Regina *et al.* 2004
FI	—	M	—	B	A	110	680	4.1	Regina *et al.* 2013
FI	2009–2011	M	15	RCG	P	73	670	6.2	**Present study**
FI	2000–2002	M	13	SB	A	100	640	4.1	Syväsalo *et al.* 2004
FI	2001–2002	O	18	grass	P	180	620	2.1	Regina *et al.* 2004
FI	2000–2002	M	13	grass	P	250	610	1.5	Syväsalo *et al.* 2004
FI	2009–2011	M	15	grass	P	153	600	4.0	**Present study**

Table A3. *(continued)*

Area	Period	Soil type	C:N	Crop	Crop cycle	Fertilizer (N)	N_2O emission	EF (%)	Reference
DK	2011	O	12	RCG	P	60	600	6.4	Karki *et al.* 2015
FI	2008–2009	M	15	SB	A	110	580	3.6	Sheehy *et al.* 2013
FI	2002	M	—	SB + WR	A	110	550	3.2	Syväsalo *et al.* 2006
FI	—	M	—	B	A	100	480	3.0	Regina *et al.* 2013
FI	2000	O	33	grass	A	—	430	—	Maljanen *et al.* 2004
FI	2002–2005	M	—	grass	P	220	430	1.3	Virkajärvi *et al.* 2010
FI	2002	M	16	rye	A	120	420	2.3	Petersen *et al.* 2006; Regina *et al.* 2013
FI	2000–2002	M	15	fallow	—	0	400	—	Syväsalo *et al.* 2004
DK	2011	O	12	SB	A	118	400	2.2	Karki *et al.* 2015
FI	2006	M	9	grass	P	70	390	3.6	Maljanen *et al.* 2009
DK	2014	O	25	O+P	A	84	370	2.8	Kandel *et al.* 2018
DE	1993	M	12	corn (row)	A	320	330	0.7	Mogge *et al.* 1999
FI	2002	M	16	rye	A	280	300	0.7	Petersen *et al.* 2006; Regina *et al.* 2013
DE	2007–2008	O	22	BF + RG	P	120	290	1.5	Beetz *et al.* 2013
FI	2002	M	16	B	A	80	280	2.3	Petersen *et al.* 2006; Regina *et al.* 2013
DE	2012	M	—	RG	P	320	280	0.6	Seidel *et al.* 2017
FI	2000–2002	M	15	grass	P	250	260	0.7	Syväsalo *et al.* 2004
DE	2013–2015	M	—	WOSR (row)	A	180	240	0.8	Ruser *et al.* 2017
FI	2002	M	16	O + pea	A	53	220	2.6	Petersen *et al.* 2006; Regina *et al.* 2013
DK	2008	M	—	WW	A	165	220	0.8	Chirinda *et al.* 2010
FI	2002	M	—	grass	P	220	190	0.6	Syväsalo *et al.* 2006
DK	2008	M	—	P/GC/WW	A	109	190	1.1	Brozyna *et al.* 2013
DK	2002	M	9.4	B	A	200	170	0.5	Flechard *et al.* 2007
DK	2014	O	24	O+SB	A	—	150	—	Kandel *et al.* 2018
DK	2008	M	—	SB/GC	A	57	140	1.6	Brozyna *et al.* 2013
FI	2002	M	16	grass	P	130	110	0.5	Petersen *et al.* 2006; Regina *et al.* 2013
DK	2008	M	—	WW	A	108	110	0.7	Chirinda *et al.* 2010
DE	2013–2015	M	—	WOSR (row)	A	180	96	0.3	Ruser *et al.* 2017
DE	2012	M	—	RG	P	280	94	0.2	Seidel *et al.* 2017
FI	2004–2007	O	42	RCG	P	60	89	0.9	Hyvönen *et al.* 2009
DK	2008	M	—	WW/GC	A	102	80	0.5	Brozyna *et al.* 2013
EE	2014	O	17	RCG	P	72	70	0.62	Järveoja *et al.* 2016
DK	2002–2004	M	9.4	RG	P	200	52	0.17	Flechard *et al.* 2007
DK	2003–2004	M	9.4	grass	P	200	45	0.14	Flechard *et al.* 2007
EE	2014	O	19	bare	—	0	34	—	Järveoja *et al.* 2016
FI	2004–2007	O	42	bare	—	0	10	—	Hyvönen *et al.* 2009