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Phosphorus - A key element determining nitrous oxide emissions from boreal cultivated peat soil

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ABSTRACT

Spatial variation in the emission rates of nitrous oxide (N_2O) and methane (CH_4) in soils can be significant due to the diverse biological, chemical, and physical conditions that influence the production and consumption of these gases. Drained organic soils are known to be hotspots for N_2O emissions, and in wet conditions they can also emit CH_4. We measured N_2O and CH_4 fluxes during the winter and growing season at 28 locations across a 7-ha area of drained organic agricultural soil in Eastern Finland. Our findings revealed expected high spatial and temporal variations in emission rates. The measured N_2O emissions varied between −0.003 and 30.4 mg N_2O m^{-2} h^{-1}, averaging at 0.94 ± 3.00 mg N_2O m^{-2} h^{-1} and CH_4 emissions varied between −0.27 and 2.90 mg CH_4 m^{-2} h^{-1}, averaging at 0.10 ± 0.33 mg CH_4 m^{-2} h^{-1}. Phosphorus concentration was identified as a limiting factor and a critical determinant of spatial variations in N_2O emissions, whereas CH_4 emissions exhibited a decreasing trend with increasing sulphur and nitrate concentrations. Our study shows that N_2O and CH_4 fluxes are linked to other elemental cycles, making it critical to identify key nutrient-related processes that govern the spatial and temporal variability in emissions of these gases.

1. Introduction

Drained peat soils, and especially those drained for agriculture, are known to be significant sources of greenhouse gases (GHG), such as carbon dioxide (CO_2) and nitrous oxide (N_2O) (Maljanen et al., 2010a; Kasimir-Klemedtsson et al., 1997). Drained peat soils can also be sources of another strong greenhouse gas, methane (CH_4), in wet conditions (Abdalla et al., 2016). Approximately 10% of agricultural soils in Finland are categorized as organic soils (more than 20% organic matter per weight in the topsoil), which include peat soils. However, despite this relatively small percentage, these soils account for 50% of the greenhouse gas emissions originating from agriculture in Finland (Kekkonen et al., 2019).

N_2O is a strong greenhouse gas, which is emitted from soils as result of microbial activity, particularly during the nitrification and denitrification processes, i.e., as an intermediate product in denitrification and a side product in nitrification (Henault et al., 2012). Drained organic soils are known to be hotspots for N_2O emissions (Hatano, 2019; Pärn et al., 2018) but the factors controlling N_2O emission rates are not fully known especially in northern soils. In agricultural soils there can be high spatial variation in N_2O emission rates because of heterogeneity of the biological, chemical, and physical conditions of the soil, which regulate processes behind N_2O production (Henault et al., 2012). Nitrogen (N) fertilization, and thus the availability of mineral N, is the key parameter in agricultural soils controlling N_2O emission rates through the stimulation of nitrification and denitrification processes (Pärn et al., 2018; Smith, 2017). Also soil moisture, soil aeration, organic matter content, pH and several other factors affect the emission rates (Henault et al., 2012). These factors can also impact the activity and composition of the microbial communities that produce N_2O, resulting in variations in emissions across different soil types. Peatlands with substantial amount of organic matter and dissolved organic carbon available as substrate for denitrification may exhibit greater potential for N_2O production (Liu et al., 2019) since denitrifying microbes require a carbon source for their energy and growth, and organic carbon serves as an electron donor in the denitrification process. One other important factor that can

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contribute to N_2O emissions is land management practices (Maljanen et al., 2010a). Agricultural practices such as fertilization, tillage and irrigation can all impact soil properties and microbial activity determining N_2O emissions. One of the key factors affecting N_2O emissions in drained peatlands is the ground water level (van Beek et al., 2010; Maljanen et al., 2010a; Martikainen et al., 1993). Deeper drainage can promote more aerobic conditions in the topsoil that enhances the activity of nitrifying bacteria producing nitrate for denitrification process, and therefore stimulating N_2O production, particularly under fluctuating water table levels that allow nitrification and denitrification to co-occur. Also, the carbon to nitrogen (C/N) ratio of peat is one of the key regulators of N_2O emissions from drained northern peat soils (Klemedtsson et al., 2005; Maljanen et al., 2010a). However, the C/N ratio does not completely explain the variation in N_2O emissions between several drained peatland sites (Maljanen et al., 2010a; Liimatainen et al., 2018).

When peat soils become waterlogged, anaerobic microorganisms break down the organic matter to produce CH_4 (Segers, 1998). CH_4 produced in peat can be released to the atmosphere through diffusion, ebullition (bubbling), or plant transport, but CH_4 can be also oxidized by methanotrophic bacteria in the aerobic top layer of peat (Segers, 1998). The spatial variation of CH_4 emissions from drained peat soils can be influenced by several factors, including the depth and extent of soil drainage, peatland characteristics, vegetation type, and management practices (Maljanen et al., 2010a). Deeper and more extensive drainage can decrease CH_4 emissions by promoting more aerobic conditions that enhance the activity of methanotrophic bacteria and oxidation of CH_4 in the uppermost peat layers.

Now there is an urgent need to find solutions to mitigate GHG emissions from peat soils used for agriculture. Finland has a target to carbon neutrality in 2035, which requires significant measures fast to reduce emissions also in agricultural sector (Ministry of Agriculture and Forestry, 2023). Therefore, understanding the key factors regulating GHG emissions is mandatory. The aim of the present study was to investigate the spatial variation in N_2O and CH_4 fluxes and ecosystem respiration and their association with soil parameters, which was achieved by comprehensive chamber and snow gradient measurements as these techniques capture small scale variation in gas fluxes. We conducted a measuring campaign using 28 sampling points evenly distributed over a cultivated peat soil field to study the emission rates of N_2O and CH_4 and associated soil biogeochemical properties on organic agricultural soil. Ecosystem respiration (CO_2) was determined simultaneously. We hypothesize that the availability of mineral N, organic matter content and soil moisture are the key factors behind N_2O emissions, but that CH_4 emissions will mainly depend on peat soil moisture instead of nutrient availability.

2. Materials and methods

2.1. Study site and agricultural practices

The study site is in Kuopio, Maaninka (63°09′N, 27°11′E), Eastern Finland. The total area of the site is about 7 ha, and it is a research field of the Natural Resources Institute Finland (Luke) and owned by a private landowner (Fig. 1). The soil type is classified as peat or histosol since organic matter content varied from 40 to 69% in the uppermost 0–20 cm layer. The peat depth in the center of the site is more than 1 m, and on the edges the peat depth varies between 0.63 and 0.80 m. The peat was well decomposed, the degree of decomposition was between 9 and 10 according to von Post scale (Von Post, 1922). The site has been drained with open ditches about 90 years ago, and an underground drainage system (pipes were installed at 20 m intervals at depth of 0.88 m) has been constructed in 1982. Prior to this study, the field was used for cultivation of grass and cereals. In 2020, grass (a mixture of Timothy *Phleum pratense* L. and Meadow fescue *Festuca pratensis* Huds.) was grown on the site but on September 22, 2020, the site was sprayed with glyphosate and in early summer 2021 a new grassland was established by using a wheat (*Triticum aestivum* L.*)* - oat (*Avena sativa* L.*)* mixture for whole crop silage as a cover. The site was ploughed on June 7, 2021, and sowing was done on June 9, 2021, with the wheat-oat mixture (175 kg ha^{-1} and 80 kg ha^{-1}) and a grass mixture (Timothy 16 kg ha^{-1} and Meadow fescue 4.5 kg ha^{-1}). During sowing the site was also fertilized with 400 kg ha^{-1} Yara Mila Y6 containing 60 kg N (42% ammonium and 58% nitrate), 26 kg phosphorus (P) and 50 Kg potassium (K) and additional K fertilization application in potassium salt, containing 25 kg K ha^{-1}. The amount of fertilizer used in the field was calculated based on the soil analysis, the crop's nutrient needs and the nutrient limits used in Finland. The P fertilization rate was based on soil P status by ammonium acetate extraction P (P_{AAC}; Vuorinen and Mäkitie, 1955) being 'fair' or 'satisfactory' (Finnish Agri-Environmental Scheme; Ministry of Agriculture and Forestry, 2015). The weed control was done by spraying Mixin ® (ADAMA, The Netherlands) on July 7, 2021. The entire crop, comprising a mixture of wheat and oats, was harvested subsequent to the ear emergence on July 28, 2021.

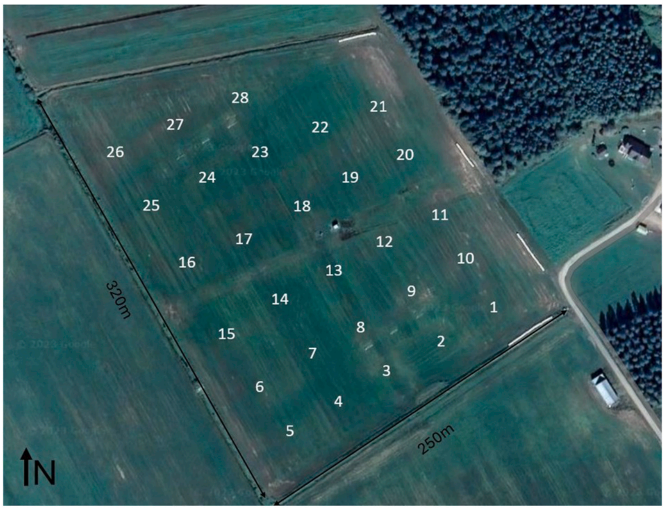

Fig. 1. Aerial photo (Google maps April 14, 2023) of the 28 sampling points on the measurement field. Numbers show the location of each sampling point, and the arrow shows north. The site has an underground drainage system and open ditches surround the field.

2.2. Climatic conditions

The site is located in the boreal climatic zone. Mean air temperature (3.8 °C) and annual precipitation (622 mm), measured from a weather station located 7 km from the study site, in year 2021 were very close to the long-term averages, 3.8 °C and 617 mm, respectively (reference period 1991–2020, Jokinen et al., 2021). The warmest month in the area has been July (17.1 °C) and the coldest February (−8.4 °C) (Jokinen et al., 2021). The snow cover typically lasts from late November until the end of April. In 2021 the snow cover disappeared in early April and the soil was completely thawed at the end of April. Wintertime soil temperature (depth 5–30 cm) under the snow cover remained rather constant close to 0 °C even when air temperatures dropped down close to −30 °C (Fig. 2).

2.3. Experimental design

A total of 28 sampling points were established evenly spaced in a grid on the study site (Fig. 1). Gas flux measurements from these locations were conducted four times during the winter period between January and March 2021 and four times from snow free soil between April and August 2021. Soil samples were taken three times in 2021 for the analysis of basic soil properties. In addition, soil cores down to 1m depth

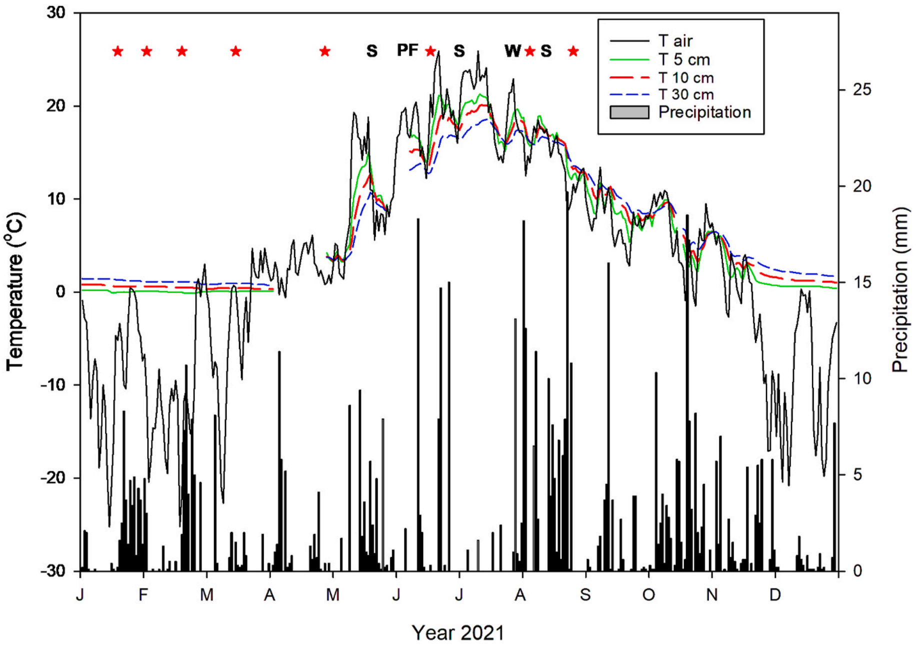

Fig. 2. Mean daily air temperature and daily precipitation measured at weather station about 7 km from the site and mean daily soil temperatures measured in the middle of the field (note the gaps in the soil temperature data). Stars indicate gas flux measurements, S = soil sampling, PF = ploughing and fertilization, W = weed control.

were drilled from each sampling point in October 2020 to measure peat depth and peat properties.

2.4. Greenhouse gas measurements during winter

During the winter period, snow gas gradient method was used to determine gas fluxes from the soil through the snow into the atmosphere (Sommerfeld et al., 1993). Snow gradient sampling was done four times between January and March 2021 (18.1., 1.2., 17.2., and 16.3., Fig. 2). Gas samples (25 ml) were carefully drawn from the snowpack with a metal probe (length 1m, inner diameter 3 mm) into a syringe and injected into pre-evacuated Labco ® 12 ml vials for concentration analysis with a gas chromatograph (Agilent 7890B, Agilent Technologies Deutschland, Germany) equipped with flame ionization (FI), electron capture (EC), and thermal conductivity (TC) detectors. Compressed air containing 2.02 ppm CH_4, 398 ppm CO_2 and 0.836 ppm N_2O was used for daily calibration. Snow depth, snow porosity, and air and snow temperature were measured from each sampling point to calculate the diffusive flux according to Sommerfeld et al. (1993). We took gas samples every 10 cm from the surface to check the linear increase in gas concentrations. The snow depth during the measurement days in winter at individual sampling points varied between 10 and 65 cm and snow porosity between 0.74 and 0.85.

2.5. Greenhouse gas measurements during the snow free period

Fluxes of N_2O, CH_4 and CO_2 were measured simultaneously with a static dark chamber method between April and August 2021. The chamber measurements with two replicate chambers on each sampling point were made once at the end of April before the growing season, once at the end of June and twice in August 2021 during the growing season (28.4., 18.6., 5.8., 26.8., Fig. 2). The chamber was a galvanized steel cylinder (diameter 30 cm, height 30 cm, volume 21 dm^3) covered with a gas tight plastic lid with two holes closed with rubber septa. Before sampling the holes were opened and the sharp edge of the chamber was twisted into the soil about 3 cm. Gas concentrations were analyzed with a gas chromatograph similarly as described for winter measurements and the gas flux rates were calculated from the linear increase or decrease of the gas concentrations in samples taken from the headspace of the chamber at 5, 10, 15, and 20 min after chamber enclosure. Close to zero CH_4 or N_2O fluxes were not omitted if CO_2 concentration was increasing linearly ($R^2 > 0.8$). The CO_2 flux measured here, i.e., ecosystem respiration, is the instantaneous emission of CO_2 from decomposition processes, respiration of soil animals and microbes, dark respiration of plants, and root respiration, as a distinction from net CO_2 exchange, which also includes photosynthesis.

2.6. Soil characteristics

Samples for analysis of mineral N, pH, electrical conductivity (EC), gravimetric moisture (GM), and water holding capacity (WHC) were collected three times using a soil corer (Ø 5 cm) during the growing season 2021. Three soil samples (depth 0–20 cm) were collected from each location and pooled. Soil gravimetric moisture content was determined by oven drying at 65 °C for 24h and organic matter content by loss of ignition at 550 °C. Soil pH and electrical conductivity (EC) were measured from soil:H_2O suspension (1:2.5). Ammonium (NH_4^+-N) analysis was made from 1M KCl-extracts spectrophotometrically (Fawcett and Scott 1960). Nitrate (NO_3^-) concentrations were measured from water extracts with an ion chromatograph (Dionex ICS-2100, Thermo Scientific). Soil bulk density (BD) was measured using volumetric cylinders, and particle density (PD) was determined with pycnometers. Soil temperature at a depth of 5 cm as well as air temperature were measured during the snow free season from each sampling point simultaneously with the gas flux measurements. Soil samples drilled in October 2020 (one soil sample drilled from each location, corer Ø 20 cm, depth 30 cm) were used for analysis of cation exchange capacity (CAC) and for analysis C and N and for basic elements (P, K, S, Ca, Mg) according to Vuorinen and Mäkitie (1955). P, K, Ca and Mg were analyzed from acid ammonium acetate extraction. The mean values of the soil analysis are shown in Supplement Table 1.

2.7. Statistical methods

The correlations between measured gas flux rates (mean flux values from each sampling point) and soil parameters were tested with nonparametric Spearman rank correlation since the gas flux data was not normally distributed according to the Shapiro Wilk normality test (IBM SPSS Statistics 27).

To determine links between N_2O fluxes and the extensive dataset of soil physical-chemical properties we conducted a principial component analysis (PCA). Prior to PCA, all variables were checked for normal distribution and the occurrence of outliers using boxplots, density- and Q–Q-plots, and CH_4 fluxes were log-transformed to fit assumptions for normal distribution. For the PCA, we used mean fluxes of each sampling point from measurements conducted in summer as well as in winter. All variables were scaled and centered before analysis to fit unit variance. We included five components, determined via Scree plot and setting the percentage of how much each individual would contribute towards explaining the PCA if all components contributed equally as a cut-off for inclusion of components. The five included components explained 82.5% of the variance, among which component 1 and component 2 explained 37.8% and 20.6%, respectively. Loadings were considered important if they were greater than 0.22 (Supplement Table 2). PCA analysis was conducted in R version 4.2.1 (R Core Team, 2022) using packages FactoMineR (Lê et al., 2008) and factoextra (Kassambara and Mundt, 2020).

3. Results

We observed a high temporal variation in GHG fluxes (Fig. 3). The N_2O emissions in all measurements varied from small uptake to high emission (Fig. 4, Supplement Table 3). During winter the N_2O emissions were at a lower level than during the snow free period but not negligible (Fig. 3). After ploughing and fertilization there was up to two orders of magnitude increase in N_2O emissions (Fig. 3).

Several sampling points emitted CH_4 during winter and during the snow free period (Fig. 3), but also a small CH_4 uptake was observed from some sampling plots, especially in late August. The highest CH_4 emissions were measured after ploughing and fertilization in June (Fig. 4).

The measured ecosystem respiration rates were the highest in early August and the lowest during winter, in January (Fig. 3). Ecosystem respiration was about 20 times lower in winter than in snow free period (Fig. 4, Supplement Table 1). During the snow free period, ecosystem respiration increased with increasing soil temperature at 20 cm and decreased with increasing soil moisture (Supplement Table 2). For the winter period we did not have soil moisture or temperature data from individual sampling points since the topsoil was frozen. In general, there was less spatial variation in ecosystem respiration rates than in CH_4 and N_2O emissions (Fig. 4).

The PCA indicated several controlling factors regulating N_2O and CH_4 emissions. In the range of the C/N ratios here (from 14.2 to 16.3) N_2O emissions increased with decreasing C/N ratio (Fig. 5). N_2O emissions also grouped closely with peat ammonium acetate extractable P (P_{AAC}) concentrations (Fig. 5) and displayed positive correlation (Supplement Table 4, Fig. 6). Soil bulk density was also associated with N_2O emissions but there was a negative correlation between soil moisture content and N_2O emissions (Supplement Table 4, Fig. 5). CH_4 emissions increased with soil pH but decreased with increasing sulphur and nitrate concentration. CH_4 emissions did not correlate with soil moisture (Fig. 5, Supplement Table 4). Peat depth did not correlate with any of the variables, and it was excluded from the PCA analysis.

4. Discussion

We identified various factors that may, to some extent, account for the spatial and temporal fluctuations in N_2O and CH_4 emissions in northern arable site with organic soil. N_2O emissions were rather constant during winter and early spring, but especially in June, after soil ploughing and fertilization, N_2O emissions increased almost 100-fold compared to earlier and late summer emissions. Similarly, CH_4 emissions increased in some sampling points after the ploughing and fertilization treatment. These agricultural practices have been reported to enhance emissions (e.g., Drewer et al., 2017; Koga et al., 2004). However, since we did not have control areas, we cannot quantify the increase in emissions due to the aforementioned measures. Ecosystem

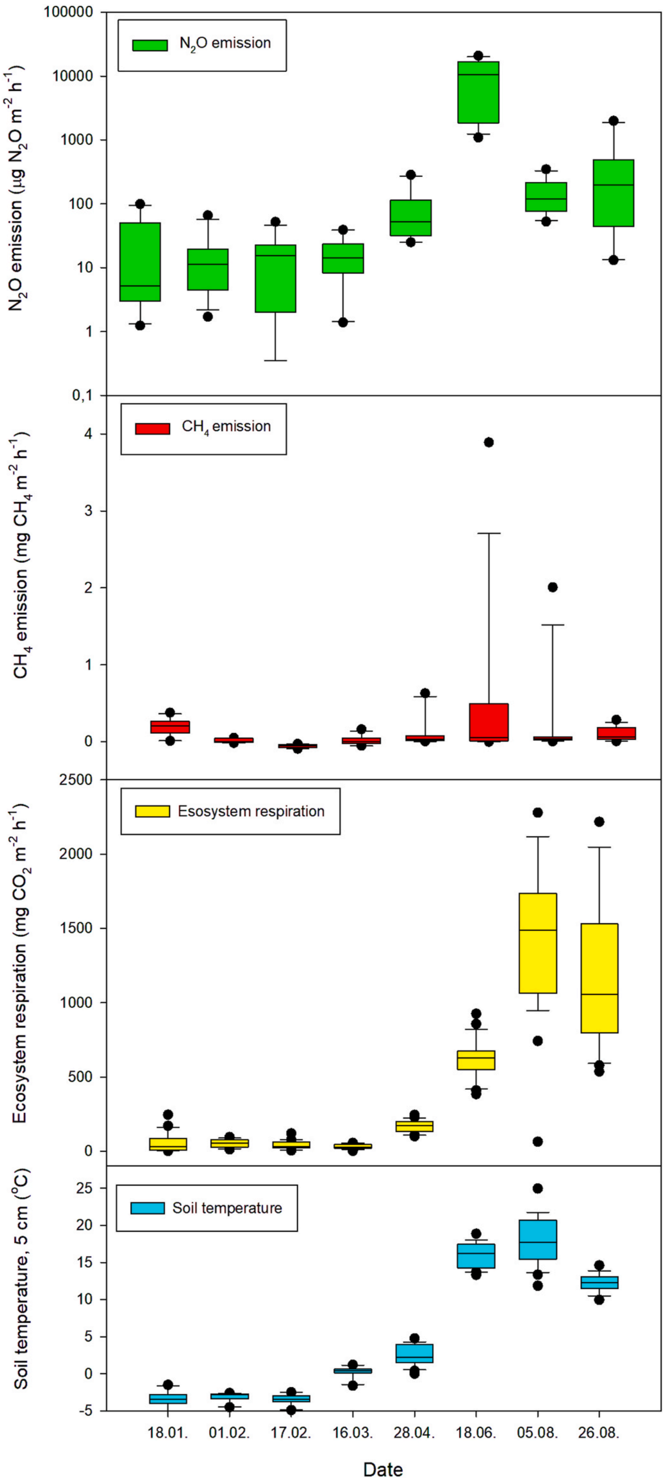

Fig. 3. Temporal variation of N_2O and CH_4 fluxes, ecosystem respiration and soil temperature at depth of 5 cm during the sampling days except winter-time soil temperature that was measured from snow-soil interface under snowpack. Note the logarithmic scale for N_2O emissions and categorical scale for sampling days. All data from 28 sampling locations included. Horizontal lines are showing the median, boxes the interquartile range, whiskers error bars and dots outliers.

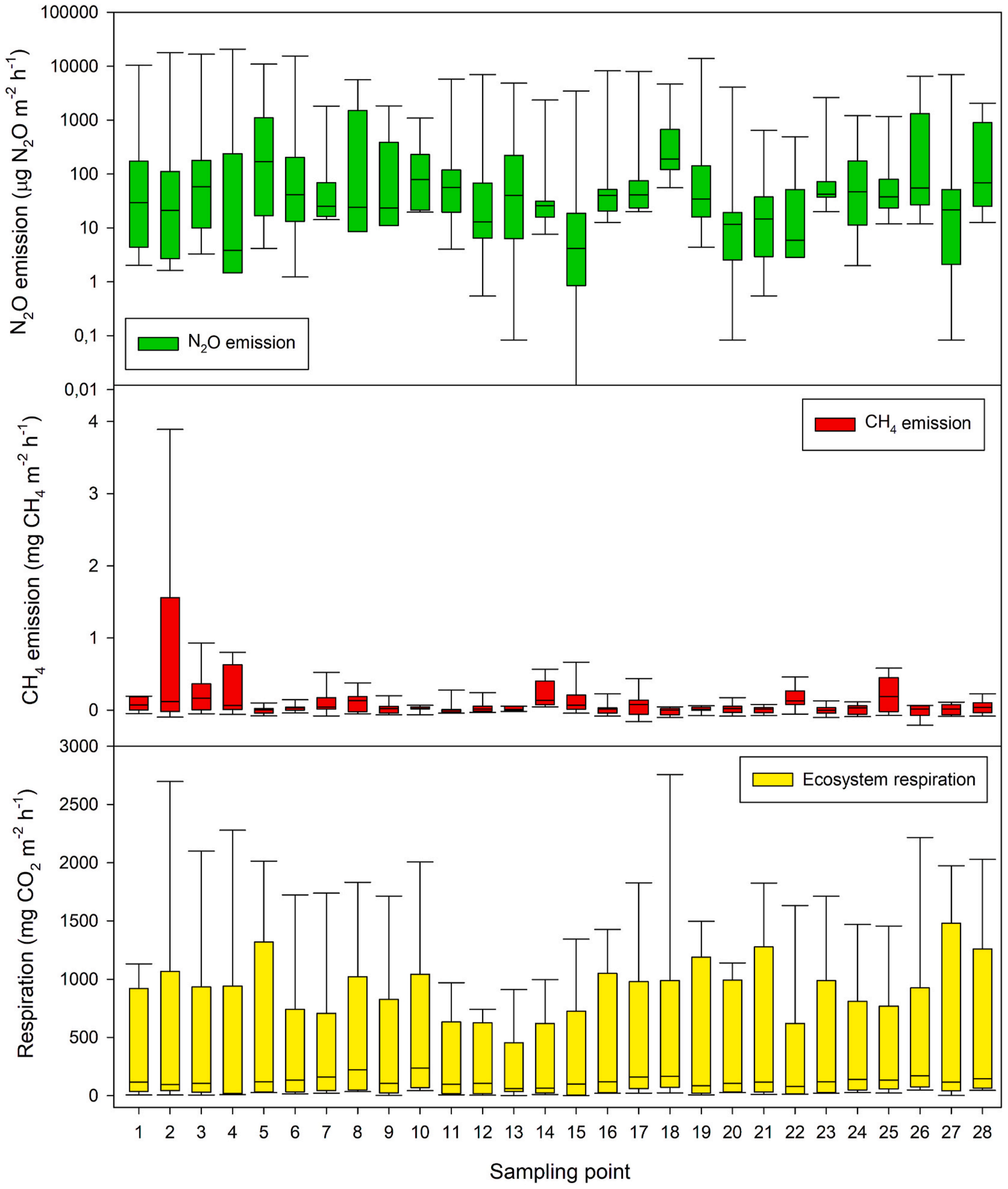

Fig. 4. Spatial variation of N_2O and CH_4 fluxes and ecosystem respiration. Data from all eight sampling times are included in the boxplots. Note the logarithmic scale for N_2O emissions. Horizontal lines are showing the median, boxes the interquartile range, and whiskers error bars.

respiration showed less variation during the study period compared to N_2O and CH_4 fluxes. We acknowledge that our measurement campaigns may have missed thawing related emissions, which can be substantial in boreal soils (Maljanen et al., 2009, 2010b).

Higher N_2O emissions were more visible at the southern part of the field. In the PCA analysis the sampling points from the southern and northern side of the field grouped on opposing sides of the PCA plot, which may indicate some systematic difference between these sampling areas. The soil C/N ratio has been considered as one of the key factors regulating N_2O emissions from drained peat soils (Klemedtsson et al., 2005; Maljanen et al., 2010a; Liu et al., 2019). In our study the variation in soil C/N ratio was narrow (from 14.3 to 16.3) and therefore the C/N ratio did not explain well the variation in N_2O emission. When N_2O emissions from individual sampling points were compared to soil properties (Fig. 5) it seems that the soil biological activity in general (ecosystem respiration) was closely linked to N_2O emission. Respiration consumes soil oxygen and therefore creates favorable conditions for denitrification as an anaerobic process and in several studies a correlation between respiration and N_2O emissions have been reported (e.g. Song et al., 2022). Also soil bulk density was closely linked to N_2O emissions. In the study of Liu et al. (2019) BD explained more than 50% of N_2O emissions from peat soils. In our study, the higher BD may indicate more decomposed peat and more anaerobic microsites for denitrification and N_2O production. Surprisingly, in our study, soil gravimetric moisture correlated negatively with N_2O emissions. We assume that relatively wet conditions during the snow free period may have limited nitrification or caused denitrification to be complete when N_2O was reduced to N_2. Here, the soil mean NO_3 concentration was not closely associated with mean N_2O emissions (Fig. 5, Supplement Table 3). The NO_3 concentration in soil is a dynamic variable and it was not measured on the same day as gas fluxes. However, NO_3 concentration is not always connected to N_2O emissions (e.g. Senbayrama et al., 2012). High NO_3 concentration could indicate high N_2O production via denitrification, but on the other hand, low NO_3 concentration could be

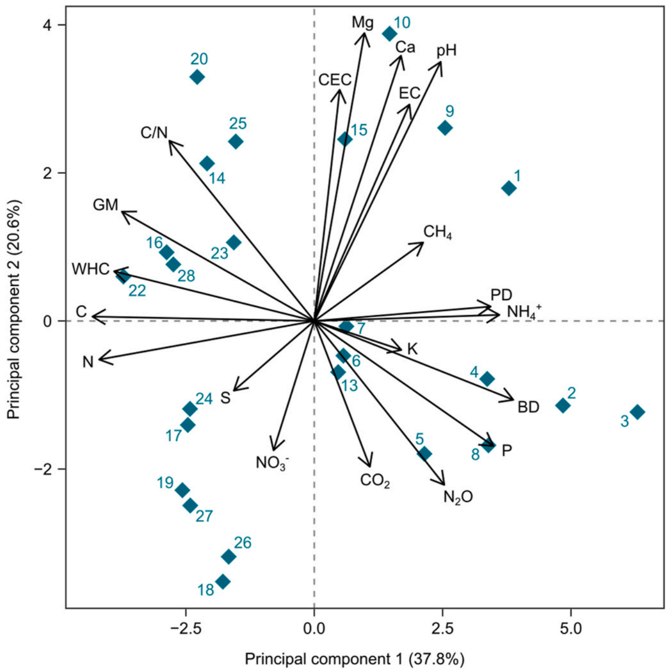

Fig. 5. Principal component analysis of N_2O fluxes, gaseous C-fluxes, and soil physical-chemical properties at the study site. Variables are shown as black arrows, whereas numbered diamond shapes denote the location of the individual measurement plots in relation to each other and the variables. Variable names: N_2O = nitrous oxide emission, CO_2 = ecosystem respiration, CH_4 = methane flux, NO_3^- = nitrate concentration, NH_4^+ = ammonium concentration, P = phosphorus (as P_{AAC}, ammonium acetate extraction) concentration, S = sulphur concentration, Ca = calcium concentration, Mg = magnesium concentration, K = potassium concentration, pH = soil pH (H_2O), BD = soil bulk density, N = soil nitrogen concentration, C = soil carbon concentration, C/N = soil C to N ratio, WHC = water-holding capacity, GM = gravimetric soil moisture, CEC = cation exchange capacity, EC = soil electrical conductivity, PD = particle density.

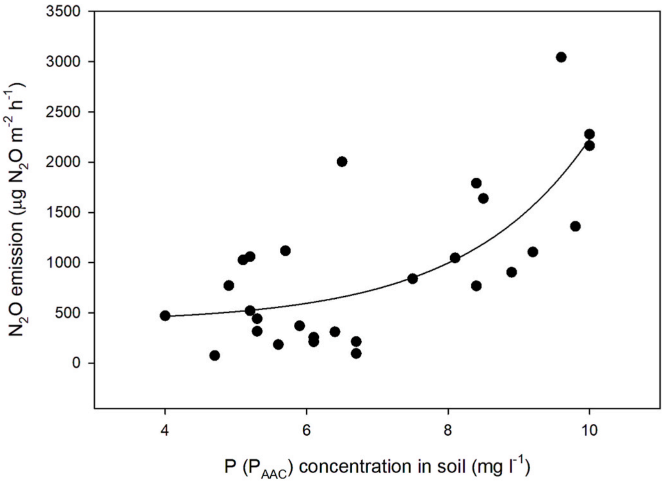

Fig. 6. Average N_2O emission plotted against phosphorus (P_{AAC}, ammonium acetate extraction) concentration in topsoil (0–30 cm) measured from the individual 28 sampling points. The fitted curve is form of $y = 402.8 + 6.563{*}\exp(0.563{*}x)$, $R^2 = 0.543$.

result of high N_2O production if all available NO_3 is immediately used in denitrification.

Interestingly, we found that P availability was one of the key factors regulating N_2O emissions, similarly as reported by Liimatainen et al. (2018) and Regina et al. (1996) for northern drained peat soils. Recently Wang et al. (2022) have also shown in their global meta-analysis that P addition accelerates soil N cycling processes, including gross N mineralization, gross nitrification, and denitrification and therefore also N_2O emissions. Similarly, Ullah et al. (2016) and O'Neill et al. (2022) showed that together with N-fertilization P application enhances N_2O emissions from mineral agricultural soil. However, the effect of P on N_2O emissions in general is not straightforward and shows complex interactions with the N-cycle. In their global meta-analysis covering natural ecosystems on mineral soils Shen and Zhu (2022) found that when the availability of N is low the added P can lower N_2O production by decreasing soil NO_3–N availability due to enhanced plant N uptake. However, in our study site on a cultivated peat soil rich in mineral N, N is not a limiting factor for plant growth and therefore P can be the limiting element. An increasing availability of P, rather than N, can drive increased N_2O emissions. The soil P_{AAC} was on a typical level when compared to Finnish organic soils used for agriculture (median 7.2 mg P_{AAC} dm^3 of soil; Lemola et al., 2018). Furthermore, the P fertilization was set according to current Agri-Environmental scheme (Ministry of Agriculture and Forestry, 2015). Therefore, the results represent reasonably well the organic soils and their management in Finland. An excessive application of P, which was not the case here, can also lead to changes in soil microbial communities and nutrient availability, which can in turn affect N_2O emissions. Further research is needed to better understand these relationships between the P and N cycle, and their implications for agricultural productivity and environmental sustainability of drained peatlands.

The studied points were mainly sources of $CH_{4,}$ but occasionally CH_4 uptake was measured from some locations in later summer. There were high emitting points in the southern end of the field (points 2,3,4) which also had high NH_4^+ concentrations. Overall, the highest CH_4 emissions were measured in June, after N-fertilization. These could be related to the inhibition of methane oxidizers (methanotrophs) by ammonia (King and Schnell, 1994). In PCA it seemed that total sulphur (S) and NO_3- are located opposite to CH_4, which could be the result of an inhibitory effect of sulphate (SO_4^{2-}), which is strongly linked to total S (e.g. Ledesma et al., 2016), and NO_3- as alternate electron acceptors, limiting CH_4 production via methanogenesis (McCartney and Oleszkiewicz, 1993). These CH_4 emissions can also be the result of a heavy rain event prior to gas flux measurements (Fig. 2).

The measured emissions are only snapshots of field condition at the time of sampling. Therefore, it is difficult to compare our measured fluxes with other studies reporting emissions measured throughout the year. However, the N_2O emission rates measured here, including measurements after ploughing and fertilization, were clearly higher than the emission rates reported from similar peat soils cultivated with grass or cereals in Finland (Nykänen et al., 1995; Maljanen et al., 2003, 2004, 2009; Regina et al., 2004; Mustamo et al., 2016). If we compare the warming effect of average CH_4 emissions (0.096 mg m^{-2} h^{-1}) and average N_2O emission (0.942 mg m^{-2} h^{-1}) by converting these emissions to CO_2 equivalents (GWP values for 100-year time horizon 28 and 265 for CH_4 and N_2O, respectively, Forster et al., 2023), then N_2O has a 100 times higher warming effect at our field (250 mg CO_2 eq m^{-2} h^{-1}) than CH_4 (2.69 mg CO_2 eq m^{-2} h^{-1}). Thus, CH_4 emissions at our site are negligible compared to N_2O emissions. We did not conduct measurements of net CO_2 exchange, which includes CO_2 uptake during photosynthesis. Consequently, we are unable to directly compare the complete warming effect of CO_2, which is considered the dominant GHG on drained organic soil, with the warming effect of N_2O and CH_4 emissions. Previous studies have indicated that N_2O accounts for approximately 10% of the total emissions from organic agricultural soils, when expressed as CO_2 equivalents (Maljanen et al., 2010a), while CH_4 only has a minor role.

5. Conclusion

This study shows the high spatial variation in N_2O and CH_4 emissions in agriculturally used peat soil and soil properties affecting these emissions. The properties of the peat, such as nutrients can vary significantly at a small scale, leading to variations in GHG emissions. Our study points towards the relevance of P supply for N cycling in this ecosystem, with higher P concentrations promoting N_2O release. Further research is required to better understand whether optimizing and restricting P fertilization could potentially mitigate high N_2O emissions from organic agricultural soils. Our study also shows that when chamber measurements are conducted only on a few locations over an organic agricultural soil, there is a high risk of biased results due to high spatial variability in CH_4 and N_2O emission rates. In addition, wintertime emissions should not be neglected. The crucial insights obtained here should be considered when designing study set-ups to capture the representative emissions over the study site.

CRediT authorship contribution statement

Marja Maljanen: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Yu Zheng:** Writing – review & editing, Investigation. **Minna Pääkkönen:** Writing – review & editing, Investigation. **Carolina Voigt:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Arja Louhisuo:** Writing – review & editing, Supervision, Data curation. **Perttu Virkajärvi:** Writing – review & editing, Supervision, Resources, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.soilbio.2024.109483.

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