Exploring temporal and spatial variation of nitrous oxide flux using several years of peatland forest automatic chamber data

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Abstract: The urgent need to mitigate climate change has evoked a broad interest in better understanding and estimating nitrous oxide (N_2O) emissions from different ecosystems. Part of the uncertainty in N_2O emission estimates still comes from an inadequate understanding of the temporal and small-scale spatial variability of N_2O fluxes. Using 4.5 years of N_2O flux data collected in a drained peatland forest with six automated chambers, we explored temporal and small-scale spatial variability of N_2O fluxes. A Random forest with conditional inference trees was used to find immediate and delayedtime-lagged relationships between N_2O flux and environmental conditions across seasons and years with different environmental conditions.

The spatio-temporal variation of the N_2O flux was large, withand the daily mean N_2O flux varyingvaried between –1011, and +1760 µg N_2O m^{-2} h^{-1} and annual N_2O budgets^{-1}. Three of differentthe six measurement chambers between +60 and +2110 mg N_2O m^{-2} y^{-1}. had a maximum N_2O flux of less than 400 µg N_2O m^{-2} h^{-1}, while the fluxes in the other three chambers exceeded 1000 µg N_2O m^{-2} h^{-1}. Spatial differences in fluxesthe flux persisted through years of different environmental conditions. Soil moisture, WTL and airover time, and despite the high small-scale spatial variability, the temporal patterns of the fluxes were relatively similar across the chambers. Soil moisture as well as air and soil surface temperature were the most important variables explaining the temporal variation of N_2O fluxes. N_2O fluxes responded to precipitation events with peak fluxes measured on average 4 days after peaks inin the random forest, with lagged soil moisture and water table level. Thealso considered important. N_2O flux responded to soil wetting with a time lag of 1–7 days, but the length of the time lagslag varied in spacespatially and between seasons indicating possible interactions with temperature and other soilspatially and temporally variable environmental conditions.

The high temporal variation in N_2O flux was related to a) temporal variation inseasonally variable environmental conditions, with the highest N_2O fluxes measured after summer precipitation eventsdry-wet cycles and

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1. Introduction

Among the greenhouse gases~~,~~ whose emissions contribute to climate change, nitrous oxide (N_2O) is one of the most potent~~, is nitrous oxide (N_2O),~~ with a 100-year global warming potential 273~~260~~ times greater~~ stronger~~ than that of carbon dioxide (Forster~~Myhre~~ et al., 2021)~~., 2013).~~ A major part of N_2O~~the~~ emissions~~ of N_2O~~ originates from soils (Butterbach-Bahl et al., 2013; Davidson and Kanter, 2014). Human~~), and human~~ impact through altered nitrogen (N) cycling~~cycle~~, land use and climate change affect the soil N_2O emissions in both~~ in~~ natural and managed ecosystems (Tian et al., 2018, 2020). The urgent need to mitigate climate change has evoked a broad interest in better understanding and estimating N_2O emissions of different ecosystems (Thompson et al., 2019; Shakoor et al., 2021). However, the accurate estimation of N_2O emissions has remained a challenge and emissions estimates continue to have relatively high uncertainties (Tian et al., 2020~~2018)., 2020).~~ A large part of the uncertainty in N_2O emission estimates is due to~~comes from~~ inadequate understanding of the temporal and small-scale spatial variability of N_2O fluxes (Sutton et al., 2007; Groffman et al., 2009; Kuzyakov and Blagodatskaya, 2015; Wang et al., 2020).

N_2O is formed in multiple processes, each favored by different soil conditions (Butterbach-Bahl et al., 2013). The main processes producing N_2O in soils are nitrification and denitrification (Bollmann and Conrad, 1998; Zhu et al., 2013; Hu et al., 2015). Nitrifying bacteria turn ammonium into nitrate in aerobic conditions. Nitrate produced in nitrification can further be reduced to nitric oxide, N_2O and gaseous nitrogen (N_2) in oxygen-limited or anaerobic conditions (Wrage et al., 2001; Zhu et al., 2013; Wrage-Mönnig et al., 2018), making the availability of oxygen~~ content~~ a key control of N_2O flux (Song et al., 2019). Oxygen limitation in soil and substrate availability for microbes is affected by soil water content, which makes N_2O production also sensitive to varying soil moisture conditions (Butterbach-Bahl et al., 2013). Along with soil moisture, substrate availability is widely affected by human actions, such as fertilization, nitrogen deposition and drainage of organic soils, which are all linked to increased N_2O fluxes (Pärn et al., 2018; Tian et al., 2020; Lin et al., 2022). Soil temperature regulates microbial activity in the soil, but it also shapes microbial community composition and affects N_2O production through, for example, frost, ice formation and thaw (Holtan-Hartwig et al., 2002; Risk et al., 2013; Wagner-Riddle et al., 2017).

Temporal variation of soil conditions~~ and substrate availability~~ can lead to a high temporal variation of N_2O flux within a year (Groffman et al., 2009; Kuzyakov and Blagodatskaya, 2015). Soil freeze-thaw and dry-wet cycles are examples of changes in soil conditions shown to shape seasonal variation in N_2O emissions (Risk et al., 2013; Congreves et al., 2018). High temporal variation of N_2O flux has been shown to be typical for~~ N_2O flux in~~ several

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ecosystems (Luo et al., 2012; Molodovskaya et al., 2012; Anthony and Silver et al., 2021), but understanding related to the temporal variation of N_2O production is limited by sparse sampling intervals of manual flux measurements, lack of short-interval measurements and poor temporal coverage of data from all parts of the year (Barton et al., 2015; Grace et al., 2020). Since short periods of high N_2O fluxes can account for a substantial amount of the annual N_2O budget (Molodovskaya et al., 2012; Ju and Zhang, 2017; Anthony and Silver, 2021), capturing N_2O flux peaks and understanding the causes of temporal variation of N_2O flux are essential for estimating annual emissions accurately.

High~~Similar to temporal variation, high~~ spatial variation is also typical~~common~~ for N_2O flux ~~(Groffman et al., 2009). Estimating N_2O emissions accurately requires integrating information about the temporal~~ and ~~spatial dynamics. Variation in N_2O flux~~ occurs on multiple spatial scales~~,~~ from large-scale variation between ecosystems to small-scale variation within a few meters (Groffman et al., 2009;~~(Ojanen et al., 2010;~~ Krichels and Yang, 2019). High N_2O fluxes are typically measured in ecosystems with high N availability, such as in agricultural fields and in drained organic soils where fertilization and organic matter mineralization provide N supply for N_2O production (Maljanen et al., 2003; Reay et al., 2012; Leppelt et al., 2014; Pärn et al., 2018). Within an ecosystem, varying soil properties and conditions such as organic matter content, soil moisture or pH can create spatial variability in the N_2O fluxes (Jungkunst et al., 2012; Giltrap et al., 2014). Although the small-scale spatial variation of N_2O flux can be large and exceed the spatial variation between more distant parts of the same ecosystem (Yanai et al., 2003; Jungkunst et al., 2012; Giltrap et al., 2014), the causes of small-scale spatial variability of N_2O flux are poorly known and little studied, especially with short-interval measurements. Several questions related, for example, to the persistence of spatial patterns over time and linkages between the spatial and temporal variation of N_2O flux are little understood.

Drained peatland forests are examples of ecosystems with relatively high N_2O fluxes and high spatio-temporal variation of those fluxes (Maljanen et al., 2003; Minkkinen et al., 2020;~~Ojanen et al., 2010;~~ Pärn et al., 2018). In Finland, about 60 % of the original peatland area has been drained for forestry (Korhonen et al., 2021), which~~). The drainage~~ has resulted in a lowered groundwater level and increased N availability for N_2O production from the decomposing peat. Drainage has led~~, leading~~ to increased N_2O fluxes, especially in nutrient-rich peatland forests with a low C:N ratio (Martikainen et al., 1993; Laine et al., 1996; Klemedtsson et al., 2005). The focus of previous studies on peatland forest N_2O fluxes has been mainly on understanding the large-scale spatial variation of N_2O fluxes between different peatland forests (Klemedtsson et al., 2005; Ojanen et al., 2010; Minkkinen et al., 2020) and reporting N_2O flux ~~fluxes for the studied peatland forest sites in~~ response to forest harvesting or other forestry operations (Maljanen et al., 2003; ~~(~~Huttunen et al., 2003; Korkiakoski et al., 2019, 2020). Temporal~~The temporal~~ variation has been mainly studied with sparce~~of N_2O flux as well as its linkages to smaller-scale spatial variation of the flux are not well understood, and only one snapshot of short~~-interval chamber~~N_2O~~ measurements (Maljanen et al., 2010; ~~is available from drained boreal peatland forest (~~Pihlatie et al., 2010).

For the first time in boreal drained peat soils~~peatlands and non-agricultural boreal ecosystems~~, we use multiple~~several~~ years (2015–2019) of automated chamber N_2O fluxes to~~measured N_2O flux to gain a more comprehensive understanding of the spatio-temporal dynamics of N_2O flux. We~~ investigate the characteristics of temporal and small-scale spatial variation in N_2O flux. We~~ and~~ link the temporal variation of N_2O flux to seasonally and annually variable environmental conditions including immediate and time-lagged responses. This is done to

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provide~~form~~ a more comprehensive understanding of~~about~~ the spatio-temporal dynamics of N_2O flux and to reduce~~decrease~~ uncertainties in current and future N_2O emission estimates in boreal peatland forests and beyond.

2. Materials and methods

2.1. Site description

The flux measurements were conducted between the 1st of June, ~~made in~~ 2015 and 29th of September, ~~–~~2019 in ~~Lettosuo,~~ a drained nutrient-rich peatland forest located in southern Finland (Lettosuo, 60°38′ N, 23°57′ E). The mean annual ~~mean~~ temperature in the area is 5.2 °C~~,~~ and the mean annual precipitation ~~is~~ 621 mm according to the long-term weather record from the nearest automatic weather station (Jokioinen Ilmala, 1991–2020, 35 km from the study site).~~).~~ The site was initially~~first~~ drained in the 1930s and more intensively in 1969 to promote~~enhance~~ tree growth. Ditches were dug about 1 m deep and 45 m apart. The site was fertilized with phosphorus and potassium after the later drainage. ~~The relatively low C:N ratio reflects the fen history of the site (Table 1). Ditches were dug in 1969 about 1 m deep with 45 m spacing.~~ Drainage lowered the groundwater table~~level~~, resulting in a transition to boreal-forest-like vegetation. ~~The ground vegetation consisted mainly of dwarf shrubs (*Vaccinium myrtillus, Vaccinium vitis-idaea*) and herbaceous plants (*Lysimachia europaea, Dryopteris carthusiana*) with sedges (*Carex globularis, Eriophorum vaginatum*) and Sphagnum mosses (*Sphagnum russowii, Sphagnum girgensohnii*) in patches.~~ The relatively low C:N ratio reflects the fen history of the site (Table 1).

Before March 2016, the site was a mixed forest with an overstory dominated by Scots pine (*Pinus sylvestris*) and~~as~~ an ~~overstory, while the~~ understory dominated by~~consisted of mostly~~ Norway spruce (*Picea abies*). Both overstory~~over~~ and understory contained~~included~~ a small amount~~number~~ of downy~~Downy~~ birch (*Betula pubescens*). Overstory pines were removed during a selection harvest in ~~In~~ March 2016~~, overstory pine trees were harvested~~ (70 % of the total stem volume; Korkiakoski et al., 2020, 2023). The~~), but the~~ surroundings of the measurement chambers~~chamber~~ used in this study were harvested more lightly, and the chamber area~~. The study plots~~ continued to have a high coverage of spruce and birch. The selection harvest ~~after the overstorey pine trees were removed in the harvesting. The partial harvesting~~ did not affect N_2O fluxes according to the previous study from the site (Korkiakoski et al., 2020), and the effect of the harvest~~harvesting~~ was left out of the focus of this study.

Table 1: Soil properties at the study site. Values represent general soil properties at the study site before the selection harvest~~forest harvesting~~ was done. Data from Korkiakoski et al. (2019).

Depth	Total-N (%)	Total-C (%)	C:N	Bulk density (g cm^{-3})
Humus	1.7 ± 0.4	56.2 ± 2.3	33.2 ± 2.3	0.01 ± 0.003
0–10 cm	2.2 ± 0.2	55.2 ± 2.1	24.9 ± 2.1	0.12 ± 0.03
10–20 cm	2.5 ± 0.2	58.9 ± 1.6	23.8 ± 1.6	0.18 ± 0.02

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2.2. Automatic chamber fluxesmeasurements

The N_2O flux between the forest floor and the atmosphere was measured usingwith six automatedautomatically operating chambers. The transparent, acrylic, rectangular cuboid chambers with the dimensions 57 x 57 x 40 cm (length x width x height) were placed to sample the spatial variation of the ground vegetation composition and were located within an area of 15 x 20 m (Fig. 1). Distance to the closest ditch and trees also varied between chambers (Table S1). The chambers were placed on permanently installed steel collars that were inserted into the soil to aabout 2 cm depth of 2 cm. All the chambers closed automatically for six minutes once an hour year-round. The chambers resulting in 6 x 24 flux measurements per day. Chambers had an air temperature sensorsensors measuring the headspace temperature and a fan to mix the air inside the chamber headspace. During winters, chambers were cleaned from snow and ice every 1–3 weeks and snow depth inside the chambers was measured to account for the effect of snow depth on chamber volume. During the winter 2016–2017, extension collars were used to better allow snow to fit inside the chambers.

The N_2O concentration of the chamber headspace air was measured using a continuous -wave quantum cascade laser absorption spectrometer (LGR-CW-QCL N_2O/CO-23d, Los Gatos Research Inc., Mountain View, CA, USA) that was placed in athe measurement cabin close to the chambers (Fig. 1b).. The analyzer had an accuracy of 0.01 ppb per second, corresponding to a minimum detectable flux (Nickerson, 2016) of 0.06 µg N_2O m^{-2} h^{-1} in our chamber system. During each chamber closure, air from the closed chambersample air was pumped into the analyzer and back to the chamber headspace through plastic tubes (length 15 m, flow about 1 l/min). After each). The same chamber closure, the airflowmeasurement system, was switched to the next chamber. Ambient air was measured for at least 1 min between the chamber closures to allow concentrations in the tubes to stabilize back to the ambient level. Concentration data from the first 30 s of each chamber closure were not used in flux calculation to avoid possible pressure disturbance caused by the closing chamber affecting the flux (Pavelka et al., 2018). For more information about the automatic chamber system, see the previousalso in other studies fromcovering N_2O, CO_2 and CH_4 fluxes of the same site (Koskinen et al., 2014; Korkiakoski et al., 2017, 2020). Measurements in Chamber 6 ended six months earlier (April 2019) than measurements in other chambers due to problems in chamber functioning.

N_2O fluxes were calculated similarly to Korkiakoski et al. (2017), but by using a linear fit. The mean headspace temperature of the to the N_2O concentration change during the chamber closure and air pressure measured at the site were used in the flux calculation.. Calculated fluxes were filtered using normalized root mean square error threshold and an iterative standard deviation filter to remove erroneous fluxes resulting from chamber malfunction (. A more detailed description of the flux calculation and filtering can be found in Korkiakoski et al., 2017). Daily mean N_2O fluxes from each chamber(2020). The fact that the fans were used in the analysis because the automatic chamber system seemednot adjusted according to create an artificialthe wind conditions likely created some diurnal cycle of N_2O from which the possible natural diurnal cycle could not be separated. The artificial diurnal cycle was caused by the difference in turbulence between the ambient air and chamber headspacein the flux, as discussed previously reported for CO_2 and CH_4 fluxes at the same site (Koskinen et al., 2014; Korkiakoski et al., 2017). During calm periods, especially during summer nights, the transfer of N_2O from soil pores to the atmosphere slowed down, leading to increased N_2O concentration in the soil. When the chamber closed and the turbulence increased because of the fan,

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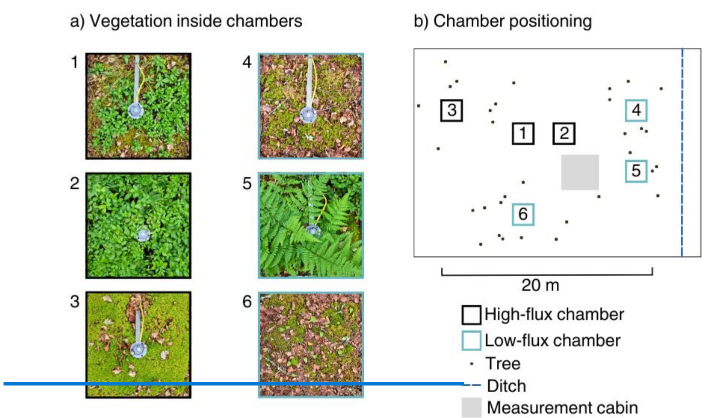
the N_2O from the soil pores was vented to the chamber headspace air, leading to overestimated flux. The opposite phenomenon probably occurred in windy conditions, resulting in underestimated flux. Based on our experience, automatic chamber fluxes measured in drained peatlands with dry and porous peat soil are particularly sensitive to ~~2017). To minimize the possible effect of artificial diurnal variation in N_2O flux, daily mean fluxes were used in~~ this phenomenon (Koskinen et al., 2014; Korkiakoski et al., 2017). Hourly N_2O flux peaks were not typical in the flux data, and daily mean N_2O fluxes thus well represent the main characteristics of the temporal variation. It should be noted that the artificial diurnal cycle creates an additional source of uncertainty in the reported N_2O budgets~~study~~.



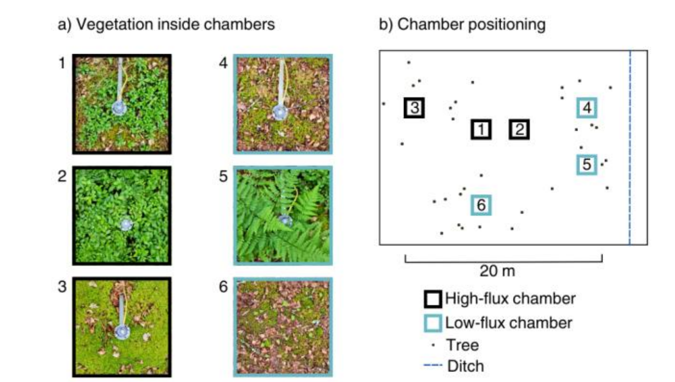


Figure 1: (~~:~~ a) Vegetation inside the six chambers and (b) the positioning of the chambers on the forest floor in relation to the nearest ditch and trees. Chambers are named from one to six based on the maximum measured flux with Chamber 1 having the highest measured flux. Chambers 1–3 with black edges are classified as "high-flux chambers" and Chambers 4–6 with blue edges as "low-flux chambers". For more information on chamber vegetation, ditches and trees, see Table S1. ~~**(Sect. 3.2).**~~

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2.3. Environmental variables

Several environmental variables were measured to link the temporal variation of N_2O fluxes with the environmental conditions. Air temperature was measured at 2 m height below the forest canopy (HMP45D, Vaisala Oyj, Vantaa, Finland). Soil surface temperature was measured at 2 cm depth in each chamber and the soil temperature at 5 cm depth at one location close to the chambers (Pt100, Nokeval Oy, Nokia, Finland). Soil moisture was measured at one location about 75 m from the chamber measurement location at 7 and 20 cm depths (Delta-T ML3, Delta-T Devices Ltd, Cambridge, UK). The soil moisture data were used to describe the temporal variation of soil moisture, assuming that the soil moisture had relatively similar temporal patterns across the study site. The ~~rather than the~~ absolute level of soil moisture in each~~at the~~ chamber may have differed from~~location. We assumed that~~ the measured soil moisture, and the possibility of differences in the temporal variation of soil moisture between the logger and ~~conditions represent the conditions near~~ the chambers cannot be excluded. Soil moisture data~~relatively well since the microtopography, surface vegetation and shading by the canopy~~ were used together with water table level and precipitation data to strengthen the conclusions related to soil water conditions. The measurements of air and soil temperatures were ongoing throughout the study period, but the soil moisture measurements ended half a year earlier than automatic chamber measurements (April 2019).~~relatively similar in both locations.~~

Water table level (WTL) below the soil surface was measured ~~hourly~~ using automatic loggers~~probes~~ (TruTrack WT-HR, Intech Instruments Ltd, Auckland, New Zealand; Odyssey Capacitance Water Level Logger, Dataflow Systems Ltd, Christchurch, New Zealand).~~) placed into dipwells that were installed into the ground.~~ Chambers 1–2 and ~~3~~ 4 5 shared a WTL logger~~sensor~~ that was placed ~~in~~ between the chamber pairs. ~~two chambers, and~~ Chambers 3 and 6 had ~~their own~~ WTL loggers~~sensors~~ next to the chambers.~~chamber collar. Since~~ WTL measurements for Chambers 3~~, 4, 5 and~~ 6 started half a year later than chamber measurements (~~in~~ December 2015).~~,~~ WTL during this and other data gaps~~before that~~ was modeled ~~for each chamber~~ using random~~Random~~ forest with conditional inference trees (Hothorn et al., 2006). WTL data from Chambers 1–2, seven other WTL loggers at the study site and ~~Other WTL measurements near the automatic chambers,~~ precipitation ~~and soil moisture~~ were used as explanatory variables in the gap-filling model. Modeling was done first for the logger with the least amount of missing data, after which the gap-filled WTL time series was added to the model as an explanatory variable to increase the predictive power of the model for the variables with more missing data~~models~~ (evaluation data $R^2 = 0.90–0.97$).

Precipitation was measured at the site throughout the study period (Casella Tipping Bucket Rain Gauge, Casella Solutions Ltd, Bedford, UK; OTT Pluvio2 L 400 RH, OTT Hydromet Ltd, Kempten, Germany) and daily ~~cumulative~~ precipitation sum was calculated.~~used.~~ The precipitation data measured at~~in~~ the nearest weather station was used to gap-fill winters and other measurement gaps in precipitation data ~~measured at the site~~ (correlation of precipitation between sites 0.65, $p < 0.05$). Snow depth ~~was~~ measured at~~in~~ the nearest weather station was~~and~~ used to describe general snow conditions experienced each winter.

Thermal seasons were used to analyze the seasonality of N_2O fluxes. The thermal seasons were defined according to typical Finnish standards (Ruosteenoja et al., 2016~~2011~~; Finnish Meteorological Institute, 2023)~~), and~~ by using air temperature data from~~of~~ the site (Appendix A). ~~During thermal winter, daily mean air temperature was persistently below 0 °C, during summer above 10 °C and during thermal spring and autumn between 0 and 10 °C.~~

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Seasons based on months were~~are~~ used to compare conditions measured at the site with ~~seasonal~~ long-term averages reported monthly for the nearest ~~automatic~~ weather station.

2.4. Identifying high-flux periods

The term “high-flux period” was used to describe periods of elevated flux, including periods from moderately increased flux to the highest flux peaks. ”High~~The term high~~-flux period” was used instead of a commonly used “hot moment” ~~term~~ because the definition of a hot moment largely varies between studies, with sometimes only extremely high fluxes being considered as hot moments (Molodovskaya, 2012; Krichels and Yang,~~et al.,~~ 2019; Anthony and Silver, 2021; Song et al., 2022).

To identify the high-flux periods, their length, seasonality and starting conditions, ~~to numerically describe the temporal patterns of N_2O fluxes,~~ different thresholds to separate high-flux days from the baseline days were tested. ~~Finally, a common percentile threshold of 70 % was used in all chambers.~~ High fluxes were measured less frequently compared to the more common low fluxes~~, which made high-flux days distinct from the more common baseline days in flux histograms of all chambers~~ (Fig. S2). Any percentile threshold between 60–80 % separated high-flux days from the more common baseline fluxes relatively well, and the mean of these (70 %) was used. ~~The mean N_2O flux of the study period was close to the chosen 70 % percentile threshold in all chambers.~~ Days with the mean flux above the 70 % percentile were classified as high-flux days and the rest of the days as baseline days. ~~.~~

The length of each high-flux period was the number of days the flux remained above the 70 % percentile, including possible data gaps within this period. The high-flux period was set to continue over a~~the~~ data gap if three days before and after the data gap were classified as high-flux days. A three-day marginal was chosen to ensure that short one-to-two-day peaks would not create long-lasting high-flux periods over ~~the~~ data gaps. If the high-flux period started from a data gap or ended to it, the start or end date of the high-flux period was set to the first or last measured day, respectively. Pearson correlation was used to test how similar the temporal patterns of N_2O flux were between chambers.

~~Pearson correlation was used to test correlation between N2O flux time series of different chambers and multiple linear regression was used to test if each environmental variable could explain differences in the flux patterns between chambers. In the multiple linear regression, N2O flux of each chamber was explained by flux of one other chamber, and ability of each environmental variable to explain the remaining variance was tested one environmental variable at the time.~~

2.5. Machine learning

Machine learning models were used to improve understanding of the temporal controls on N_2O flux, including a possible effect of time lags between environmental conditions and N_2O flux.~~. Since the models were run separately for the six chambers, the models also allowed estimation of whether the temporal variation is controlled similarly in the different chambers.~~ The machine learning approach was used because machine learning models do not rely on mathematical functions to describe relationships between variables and are able to account for interactions

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between variables flexibly (Olden et al., 2008). ~~without having to include them in the equation by hand (Olden et al., 2008). This is particularly useful when using a large dataset with multiple environmental variables to model N_2O fluxes whose controls and mathematical forms of responses are not yet fully understood.~~

The Random forest algorithm, developed by Breiman (2001), is a classification tree-based method that uses bootstrap aggregation of a model training data and a randomly chosen subset of explanatory variables (*mtry*-parameter) to train each classification tree. In bootstrap aggregation, a subset of data is taken from the model training data with or without returning it to the original training data. The part of data that is not bootstrapped to train trees is called out-of-bag (OOB)~~). OOB~~ data and it can be used to evaluate model performance.~~, since this part of the data is not used during the model training phase.~~ In each random~~Random~~ forest tree, the bootstrapped data are classified into subgroups and further into~~to~~ smaller subgroups by setting threshold values for the randomly chosen subset of explanatory variables. The setting of the threshold values is done to maximize the information gain until no further thresholds, also called splits, can be made. After a selected number of trees are built, the final model prediction can be made using the average of all the trees (continuous response) or the most common outcome (categorical response).

Random forest variable importance (VI) metrics show the importance of each explanatory variable in explaining variation in the response variable. VI~~Variable importance~~ metrics can be biased if the ~~data type and scale of the~~ explanatory variables correlate~~vary or if there is a correlation between explanatory variables~~ (Strobl et al., 2007). Therefore, we used random~~Random~~ forest with conditional inference trees (Hothorn et al., 2006) that allowed us to get more accurate VIs~~variable importance measures~~ in the presence of correlated explanatory variables and their time-lagged versions. Compared to trees in random~~Random~~ forest, conditional inference trees use a p-value-based splitting criterion to classify the bootstrap aggregated data in the building phase of each tree. As suggested by Strobl et al. (2007), in the presence of correlated explanatory variables, variable importance metrics from the conditional inference trees were calculated using conditional permutation importance.

Chamber-specific models had daily mean N_2O flux as the response variable and the measured temperature variables (air, soil 2 cm and~~,~~ 5 cm depths), soil moisture (7 and 20 cm depths), WTL and daily cumulative precipitation as explanatory variables. Periods~~Time lags~~ of missing data in environmental variables were gap-filled using the random forest proximity tool RFimpute (Liaw and Wiener, 2002). One-to-seven days' time-lagged versions of each environmental variable~~1–7 days~~ were added as ~~additional~~ explanatory variables to~~for all~~ the models besides unlagged environmental~~explanatory~~ variables. The imbalanced distributions~~distribution~~ of N_2O fluxes ~~as model predictors~~ were corrected with the SMOGN algorithm (Abd Elrahman and Abraham, 2013). The subset of data to train each tree was bootstrapped without replacement with a sample size 0.632 times the size of the training dataset, as suggested by Strobl (2007). Models were trained with 500 trees and random~~Random~~ forest default *mtry* for continuous response variable was used (*mtry* = number of explanatory variables / 3).

The first three years of data were utilized as the model training period (~~1~~ June 2015 – ~~1~~ June 2018), and this data were further split into 70 % training data and 30 % evaluation data to test model performance within the training period. The fourth year of measurements until soil moisture measurements ended (~~1~~ June 2018 – 4 April 2019) was left aside for evaluation to test model performance outside the training period. The performance~~prediction accuracy~~ of the models on different~~in each~~ evaluation datasets~~data~~ was analyzed using R squared (R^2) and root mean squared

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Commented [HR20]: Short description about gapfilling environmental variables was added error (RMSE), R^2 was used to compare model performance between chambers. Variable selection was not done. Evaluation results are presented in appendices (Appendix B).

VIs and accumulated local effects (ALE) were used to interpret the modeling results. For easier comparison of VIs across chambers, the VIs of each chamber ~~Variable importance values~~ were scaled from~~between~~ zero to~~and~~ one (0 = least important variable, 1 = most important variable) and the total VIs of each variable were calculated (total VI = VI of unlagged variable + VIs of lags). ~~to enable comparison between chambers.~~ The ALE~~Accumulated local effects (ALE)~~ method by Apley and Zhu (2020) was used to visualize the response of N_2O flux to environmental conditions and their lags in the models. In ALE figures, ALE value (y-axis) zero refers to the mean predicted N_2O flux, with a positive ALE value meaning larger and a negative value lower predicted N_2O flux in a specific environmental condition (x-axis). ALE values for lagged environmental variables indicate the response of predicted N_2O flux to previous environmental conditions. From the unlagged and lagged versions of each environmental variable, the one that received the highest ALE value for a given environmental condition was considered to represent the typical response time of N_2O flux to that condition. In this article, the response time, or lag length in the presence of at least a one-day lag, refers to the time it takes for N_2O to reach peak flux after the onset of a given environmental condition. The reported evaluation results (RMSE, R^2), VIs, and ALE values are averages over 10 model runs.~~.~~

2.6. ~~Gap-filling and~~ N_2O budgets

Data gaps covered 12–24 % of the study period depending on the chamber. Daily mean~~Most gaps occurred at the same time in all chambers. Notable is that measurements in Chamber 6 ended six months earlier in 2019 than measurements in other chambers.~~ N_2O flux time series were gap-filled to calculate N_2O budgets. Gap-~~In other analysis, gap-~~filled data were not used in other analyses to avoid additional uncertainty ~~of the results~~ arising from the gap-filling.

~~Gap-filling was done by training the Random forest with conditional inference trees on the whole measurement period (4.5 years) data with 30 % data excluded for evaluation.~~ The same models and explanatory variables were used ~~in the models~~ as in the machine learning part~~analysis~~, including time-lagged variables. The fourth measurement year previously left for evaluation was also included in the training data for gap-filling. To test the performance of the gap-filling model, separate models were run with 70 % and 30 % split to the training data and evaluation data, respectively. Evaluation metrics (RMSE, R^2)~~results~~ of gap-filling models are shown in Appendices (Appendix B). Gap-filled daily mean N_2O fluxes were used to calculate ~~cumulative~~ N_2O budgets~~flux~~ for each chamber in each thermal season~~ and year~~. The uncertainty~~uncertainties~~ related to the N_2O budgets was~~were~~ assumed to be a combination of uncertainty related to flux measurement and uncertainty related to gap-filling. Detailed information about the calculation of the uncertainty can be found in Korkiakoski et al. (2017).

Flux calculation was performed in the Python programming language version 2.7 (Van Rossum and Drake, 1995). Data preparation and analysis were performed in R statistical software version ~~1.~~4.0.5~~1~~ (R core team, 2021). Cforest-command in the party package (Hothorn et al., 2006; Strobl et al., 2007; Zeileis et al., 2008) was used to perform random~~for Random~~ forest with conditional inference trees. Data and simplified R-code about the machine learning part of the study are made freely available (See Sect. 7).

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Commented [HR22]: Explanation about how Vis are interpreted was clarified.

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3. Results

3.1. Environmental conditions

~~The seasonal temperature conditions were variable for the years 2015–2019 (Fig. 2).~~ The summers (June, July, August) 2015 ~~(14.1 °C)~~ and 2017 ~~(14.4 °C)~~ were colder (seasonal means 14.1 °C and 14.4 °C, respectively) than the long-term average (15.6 °C, Jokioinen-Ilmala 1991–2020), and~~), while~~ winters (December, January, February) 2015–2016, ~~(–3.4 °C),~~ 2016–2017 ~~(–3 °C)~~ and 2018–2019 ~~(–3.5 °C)~~ were warmer (seasonal means –3.4 °C, –3.0 °C and –3.5 °C, respectively) than the long-term average (–4.3 °C) (Fig. ~~Jokioinen Ilmala, 1991–2020).~~ 2). Temperatures were warm in all seasons in~~during the years~~ 2018 and 2019~~were warmer than the long-term average~~, with the summer (seasonal mean 17.2 °C) and autumn (seasonal mean 6.7 °C) 2018 being particularly~~especially~~ warm compared to the ~~(~~long-term averages (summer~~average temperatures~~ 15.6 °C and autumn 5.4 °C). ~~, respectively).~~

The area received the least amount of precipitation in 2018 (annual sum 434 mm) and the most precipitation in 2017 (annual sum 657 mm) with~~), when~~ the long-term annual average being~~was~~ 621 mm. The ~~Winter 2015–2016 (67 mm) was wet, while autumn 2016 (36 mm), winter 2016–2017 (24 mm) and~~ summer 2018 (seasonal sum 44 mm) was especially ~~were~~ dry compared to the long-term average summer precipitation of 71 mm. The drought that began in the spring 2018 continued until~~averages (winter 44 mm,~~ autumn. ~~58 mm and summer 71 mm).~~

Soil ~~conditions measured at the site varied between seasons and years (Fig. 3). Soil~~ moisture was~~at 7 cm was on average lower in winters (0.26 m⁻³ m⁻³) and springs (0.22 m⁻³ m⁻³) compared to summers (0.31 m⁻³ m⁻³) and autumns (0.33 m⁻³ m⁻³). Soil moistures at 7 cm and 20 cm were~~ continuously lower than the mean~~means~~ of the study~~measurement~~ period ~~(0.28 and 0.56 m⁻³ m⁻³, respectively)~~ from the summer 2018 until the end of the study~~measurement~~ period (Fig. 3), with~~. WTL was deeper than the mean of~~ the study period mean being 0.28 m^{-3} m^{-3} for 7 cm soil moisture and 0.56 m^{-3} m^{-3} for 20 cm soil moisture. WTL was on average –~~(–~~36 cm and continuously deeper than that~~)~~ in the summer and autumn 2015 as well as in the summers 2018 and 2019. ~~Soil surface temperatures varied on average between –0.6 °C in winter and 14.0 °C in summer with small differences in soil surface temperatures between chambers.~~ Soil temperatures at 5 cm depth reached freezing~~below zero~~ temperatures in winters 2015–2016 (min. –3.8 °C), 2016 –2017 (min. –1.8 °C) and 2017–2018 (min. –0.33 °C). Variation of ~~–0.33 °C) with most days with negative soil 5 cm temperatures in winters 2015–2016 and 2016–2017. Temporal variation in~~ air and soil surface temperatures was high~~greater~~ in winters 2015–2016 and 2016–2017. The ~~compared to the latter two years of the measurement period. All winters had a period or periods of~~ snow cover was thickest~~with the maximum measured snow depth being the greatest~~ in winter 2018–2019 (max. 52 cm) and thinnest~~the lowest~~ in winter 2016–2017 (max. 11 cm). The number of days with snow cover was lower in winters~~Winters~~ 2015–2016 (85 days) and 2016–2017 (93 days), and higher in~~) had days with snow cover less than~~ winters 2017–2018 (125 days) and 2018–2019 (116 days).

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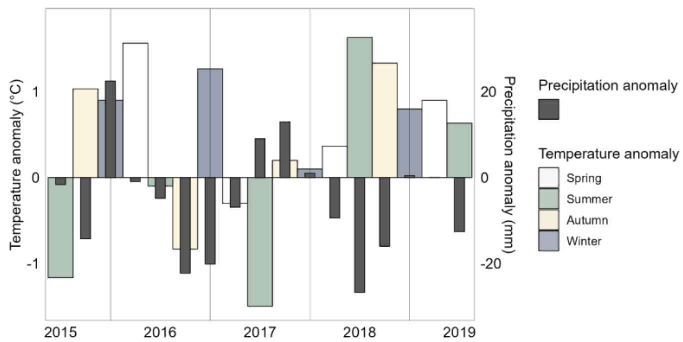

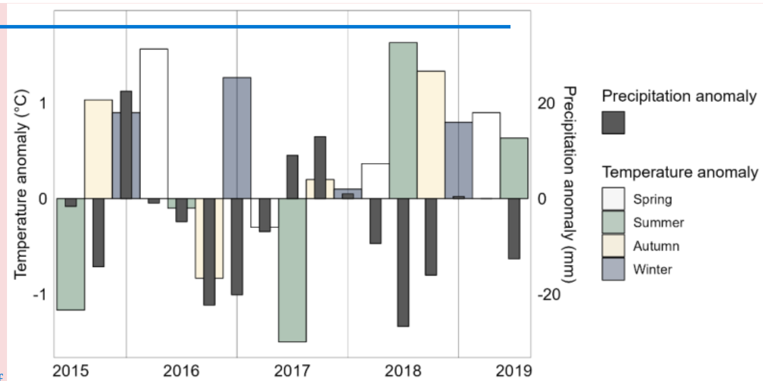

Figure 2: Difference of

Figure 2: Seasonal temperature and precipitation anomalies during the measurement period. The seasonal mean air temperature and seasonal cumulative precipitation sum from the long-term average. Theof each year is compared to the long-term seasonal averages fromat the nearest weather station are used (Jokioinen Ilmala, (1991–2020). Seasons are based on months (autumn: September–November, winter: December–February, spring: March–May and summer: June–August).

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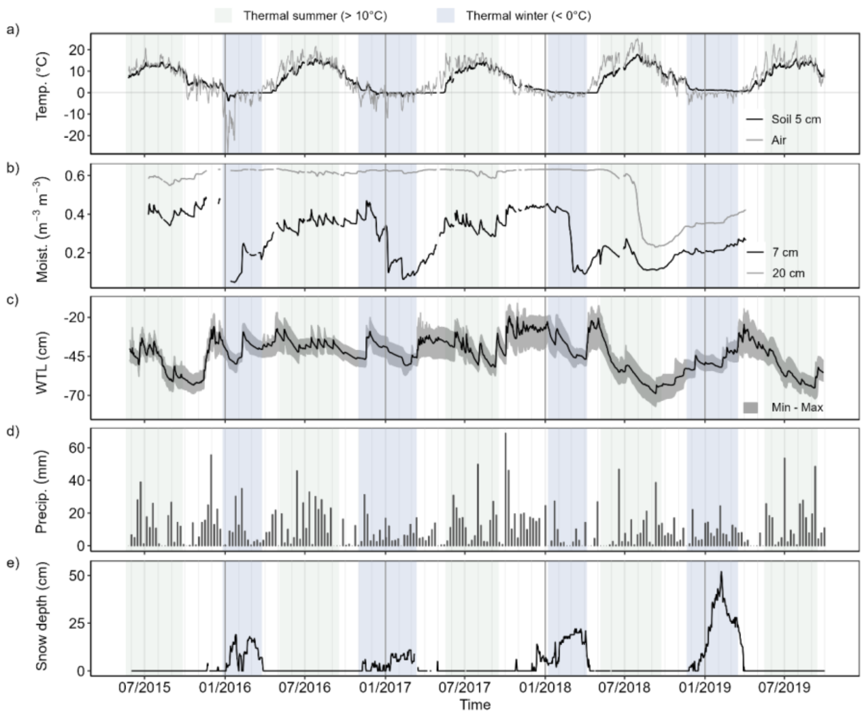
Thermal summer (> 10°C)
Thermal winter (< 0°C)
a)
Temp. (°C)
Soil 5 cm
Air
b)
Moist. (m^{-3} m^{-3})
7 cm
20 cm
c)
WTL (cm)
Min - Max
d)
Precip. (mm)
e)
Snow depth (cm)
07/2015
01/2016
07/2016
01/2017
07/2017
01/2018
07/2018
01/2019
07/2019
Time

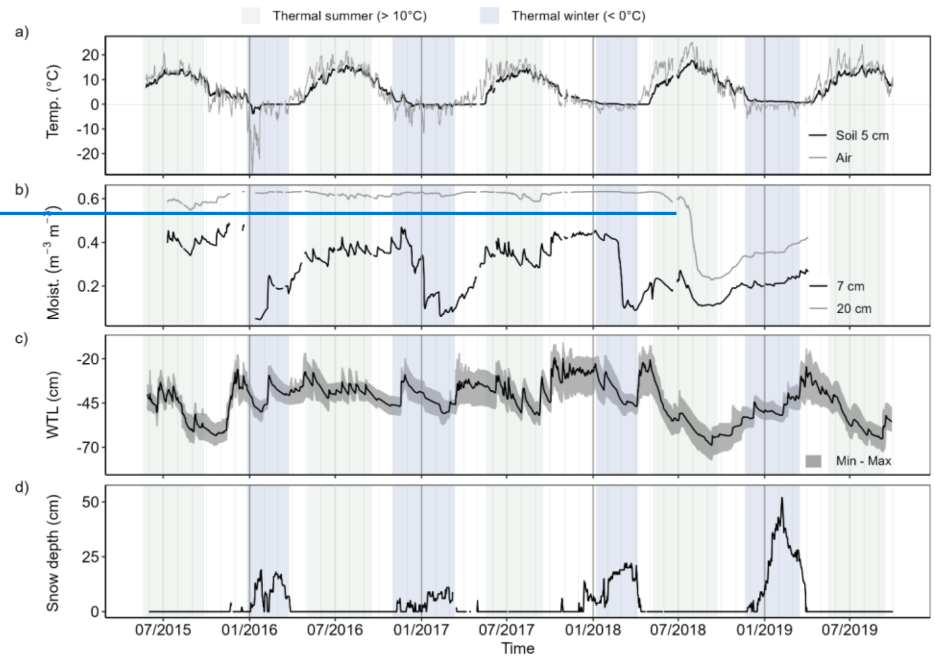

Figure 3: (a) Daily mean air and soil temperatures (5 cm depth), (b) soil moisture (7 and 20 cm depthsdepth), (c) water table level (WTL), (d) weekly precipitation sum) and (e) daily mean d) snow depth. WTL is the mean of the chambers with gray shading showingvalues measured next to the range of WTL between different chambers. with variation between the lowest and highest WTL indicated with shading. Snow depth was measured at the nearest weather station. Data are not gap-filled. For the definition of thermal winter and summer, see Sect. 2.3).

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3.2. Temporal and spatial variation of N_2O flux

The dailyDaily mean N_2O flux varied between –10 and +1760 µg N_2O m^{-2} h^{-1} during the 4.5 years of measurements (Fig. 4). 4), and chamber mean N_2O flux between +20 (Chamber 6) and +140 µg N_2O m^{-2} h^{-1} (Chamber 1) (Table 2). The annual mean flux was the highest in 2016 or 2017, depending on the chamber, and smallest in 2018 in all chambers (Table S3.1). Mean fluxes in 2015 (June–December) were lower than in the whole years of 2016 and 2017 but higher than in 2018. Mean fluxes in 2019 (January–September) were generally higher than the mean fluxes in the whole year 2018.

Three chambers (Chambers 1, 2 and 3) had maximum daily mean fluxes greaterlarger than 1100 µg N_2O m^{-2} h^{-1}, andwhile the other three chambers (Chambers 4, 5 and 6) had maximum daily mean fluxes lesssmaller than 400 µg N_2O m^{-2} h^{-1} (Table 2). Chambers 1–3 also^{-1}. The mean and the range of the daily mean N_2O fluxes varied between years and chambers, but the high-flux chambers generally had a higherrange and mean flux higher than Chambers 4–6the low-flux chambers in all years (Table S3.1). The annual Differences in the mean flux was the highestand the range of the mean daily flux between high-flux and low-flux chambers were the largest in 2016 orand 2017, depending on the chamber, and lowestthe smallest in 2018 orand 2019. Based on the differences especially in the maximum flux, standard deviationfluxes and in the range of the flux variation, Chambers 1–3 were classified as "high-flux chambers" and Chambers 4–6 as "low-flux chambers". .

The chamberChamber-specific 70 % percentiles that were used to define the high-flux periods from the baseline periods (Sect. 2.4) ranged from 20 (Chamber 5 and 6) to 170 µg N_2O m^{-2} h^{-1} (Chamber 1, Table 2). The length of the individual baseline periods varied frombetween 1 toand 330 days with a mean of 26 days, while the length of the high-flux periods varied between 1 and 134 days with thea mean of 11 days.

The correlationcorrelations of the flux time series betweenfor each pair of chambers were positive and varied between 0.79 (Chambers 1 and 2) and 0.29 (Chambers 1 and 4) (Table S4). Correlation was.1). Correlations were the highest between the chambers with a similar range of N_2O flux: among high-flux chambers, correlationcorrelations varied between 0.64–0.79 and among low-flux chambers, between 0.46–0.49. DifferencesSoil surface and soil 5 cm temperatures explained the differences in WTLN2O fluxes between chambers weremost chamber pairs statistically significant but were not associated with the spatial variation of N_2O flux.significantly (Fig. S4.2).

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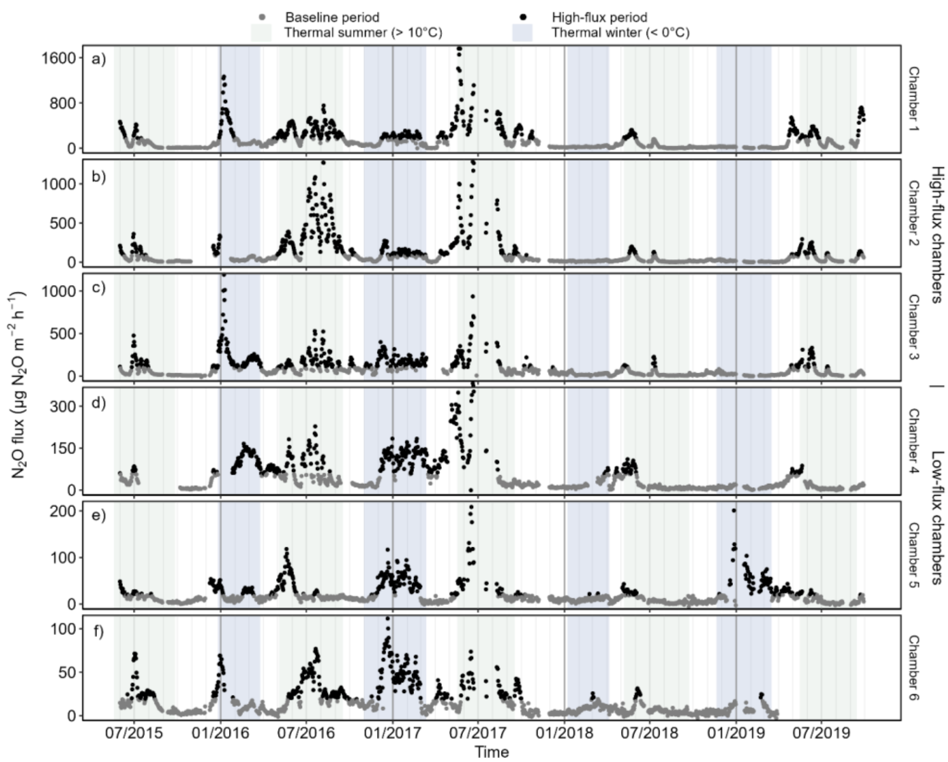
Baseline period
High-flux period
Thermal summer (> 10°C)
Thermal winter (< 0°C)
a)
b)
c)
d)
e)
f)
Chamber 1
Chamber 2
Chamber 3
Chamber 4
Chamber 5
Chamber 6
High-flux chambers
Low-flux chambers
N_2O flux (µg N_2O m^{-2} h^{-1})
07/2015
01/2016
07/2016
01/2017
07/2017
01/2018
07/2018
01/2019
07/2019
Time

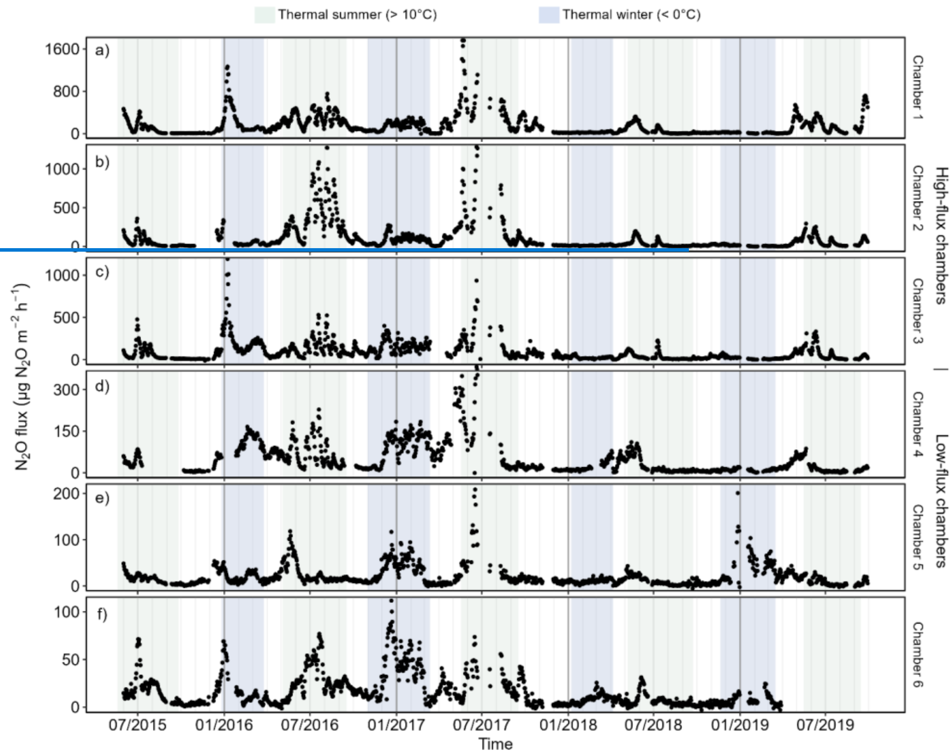

Figure 4: Daily mean N_2O flux measured in the six automatic chambers in 2015–2019. Fluxes from different chambers are shown in panels (a–f) ordered by maximum daily mean N_2O flux. Chambers are grouped into high~~low~~-flux (Chambers~~Chamber~~ 1, 2 and 3) and low~~high~~-flux chambers (Chambers~~Chamber~~ 4, 5 and 6). The scale of the y-axis is chamber specific and fluxes are not gap-filled. Periods ~~Thermal winter refers to a period~~ with the daily mean fluxes > 70 % percentile are classified as high-flux periods~~air temperature persistently < 0 °C and thermal summer to a period with daily mean air temperature persistently > 10 °C~~.

Table 2: Minimum, maximum, mean, median, 70 % percentile and standard deviation (SD) of daily mean N_2O fluxes over the study period. The unit~~4.5 years for each chamber. Unit~~ of the flux is µg N_2O m^{-2} h^{-1}. Percentile thresholds (70 %) were used to define high-flux periods. Year-specific statistics can be found in Table S3.1.

Source	Min	Max	Mean	Median	Percentile 70 %	SD
Chamber 1	–1	1761	143	73	168	193
Chamber 2	–1	1282	99	34	88	171
Chamber 3	–12	1192	87	46	100	112
Chamber 4	–1	381	48	22	58	57
Chamber 5	–5	244	20	13	20	23
Chamber 6	–3	112	17	11	19	17

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3.3. Seasonality of N_2O flux

The highest N_2Odaily fluxes were measured during the thermal summers (Chambers 1, 2, 4 and 5) or winters (Chambers 3 and 6).) depending on the chamber. The fluxesmean seasonal N_2O fluxes calculated for thermal seasons were also on average the highest infor the thermal summers andor winters, and the lowest in autumns (Tables S3). throughout the study period. The mean N_2O flux was the smallest in autumn in all years and chambers. The percentage of measurement days identified as high-flux days averaged was on average 24 % in spring, 38 % in summer and 44 % in winter and, while the thermal autumns had 9 % in autumn days identified as high-flux days (Fig. 5). The highest proportion of high-flux days in each season varied between years with the highest proportions of winter andhigh-flux days measured in 2015 and 2017, and the highest proportions of summer high-flux days were measured in summers 2016 and 2017, and the lowest proportion in 2018.. Variation in the percentage of high-flux days between chambers was greatest for thermal winters.

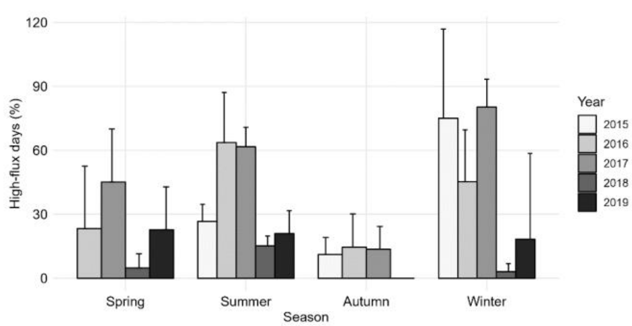

Figure 5: Mean occurrence of high-flux days out of measured days in different thermal seasons and standard deviation between chambers.

In spring, N_2O fluxes increased steadily as started to increase when soil surface temperaturestemperature increased above zero (Fig. 6 and S5), with most of the spring high-flux periods starting at soil surface temperatures 0–2 °C (Fig. 7). Spring N_2O fluxes steadily increased steadily with increasing soil temperatures, and flux peaks werepeak top was reached in late spring or early summer. SummerIncreased summer N_2O fluxes were measured after peaks in soil moisture and WTL, the highest N_2O fluxes being reached typically several days after soil moisture and WTL peak. Most summer, high-flux periods started after precipitation eventswhen soil moisture, at moist soil conditions (7 cm was 0.37–0.41 m^{-3} m^{-3}), and during relatively high WTL (–between –35 toand –50 cm depth) (Fig. 7), but the peak fluxes were reached several days after the rain events. The. Autumn high-flux period starting conditions for soil moisture and WTL in were similar to the summer, but increased N_2O fluxes were reached a longer period of time after soil moisture and WTL peak. Soil temperatures at the autumnstart of the high-flux periods were

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Winter high-flux periods started on soil temperatures close to 0 °C (Fig. 7). In early winter, ~~the~~ N_2O fluxes increased when soil ~~temperatures at the soil~~ surface temperatures~~and 5 cm depth~~ decreased ~~close~~ to near zero and below that, with further increase in flux measured if soil temperature also at 5 cm depth decreased below zero (Fig. 6 and S5). Later in~~6, 7, S5). After the initial freezing peak, early winter N_2O flux started to decrease after the soil temperatures increased close to or above zero. Later during~~ the winter, increased N_2O fluxes were measured during periods of soil freezing or when soil temperatures increased towards~~close to~~ or above zero~~after soil freezing~~. Freezing of the soil surface did not typically lead to high N_2O fluxes without temperatures being below zero also at 5 cm depth. The response to soil freezing, especially in the early winter, was stronger than the response to soil thawing in terms of duration of the high-flux periods and peak flux. ~~. An exception to that was Chamber 5 during winter 2018–2019, where high N_2O fluxes were measured during the mid-winter despite freezing temperature measured only at the surface soil. Temporal variation of N_2O fluxes within winter were also related to the temporal variation in soil surface and air temperature, with N_2O fluxes varying more in winters 2015–2016 and 2016–2017 with higher temporal variation in temperature compared to other winters.~~

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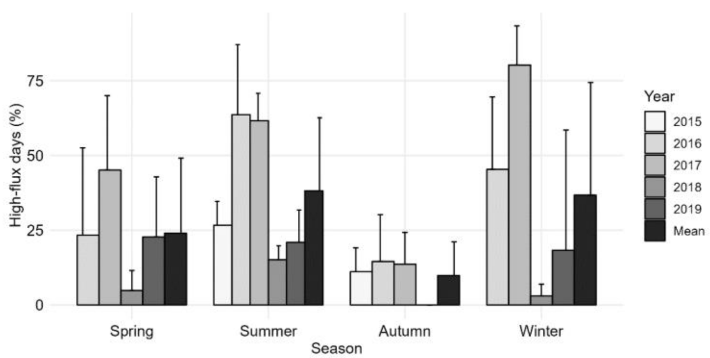

Figure 5: Occurrence of high-flux days out of measured days in different thermal seasons. Bars show annual means across different chambers and error bars show standard deviation between chambers. Mean bars show the mean across the years. The bar for winter 2019 only contains winter days between January – March 2019.

Commented [HR33]: Figure was updated: The bar for winter 2015 was removed because it contained only few days (no measurements at the beginning of 2015 and winter stated late in December). Means accross years were also added.

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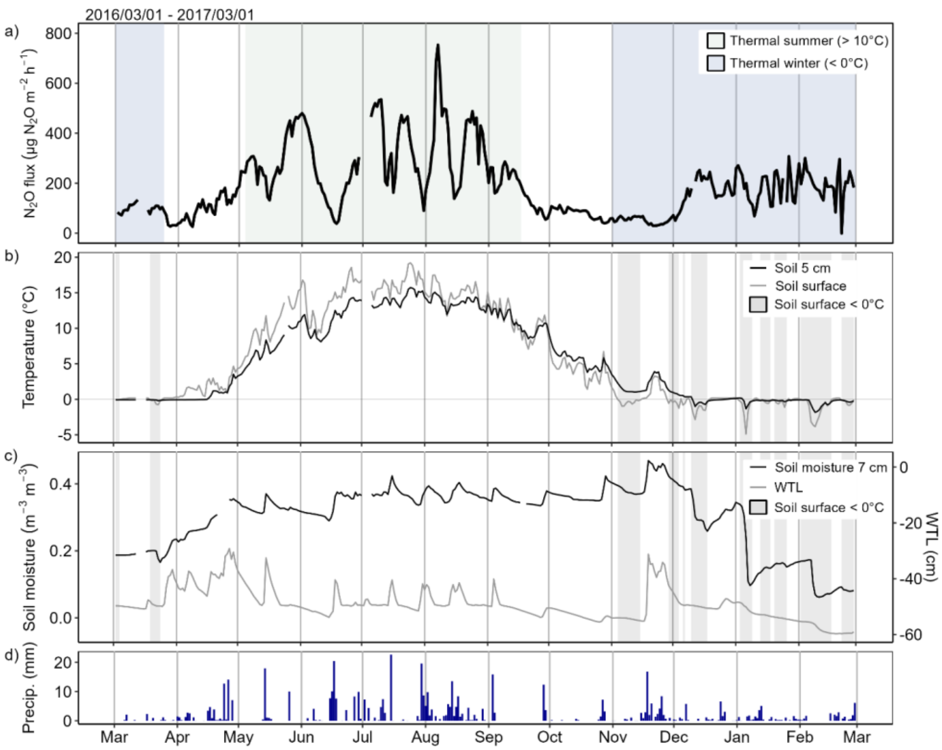

2016/03/01 - 2017/03/01
a)
b)
c)
d)
Thermal summer (> 10°C)
Thermal winter (< 0°C)
N_2O flux (µg N_2O m^{-2} h^{-1})
Soil 5 cm
Soil surface
Soil surface < 0°C
Temperature (°C)
Soil moisture 7 cm
WTL
Soil moisture (m^{-3} m^{-3})
WTL (cm)
Precip. (mm)
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar

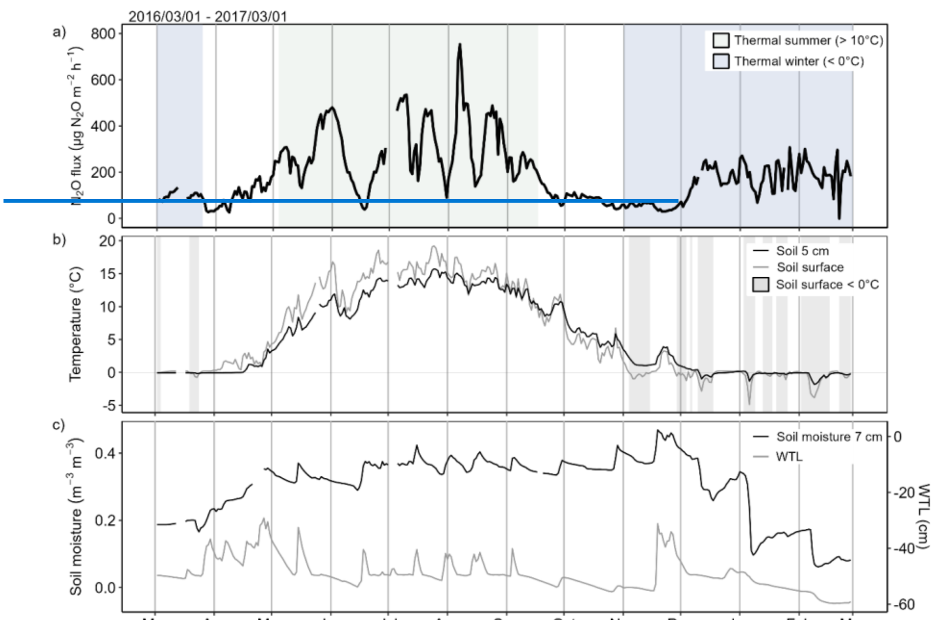

Figure 6: ~~(:~~ (a) Daily mean N_2O flux, (b) soil surface temperature and temperature at 5 cm depth with highlighted freezing periods (soil surface temperature < 0 °C), ~~(and~~ (c) soil moisture and water table level (WTL), and (d) daily precipitation~~)~~ from March~~February~~ 2016 to March 2017 in Chamber 1. The temporal variation of N_2O flux in Chamber 1 was similar to the other chambers, but the range of flux variation was larger compared to the low-flux chambers. The shown temporal dynamics of N_2O flux were measured in a year with relatively wet summer and warm winter. Data are not gap-filled. Figures for other chambers are presented in the supplements (S5).

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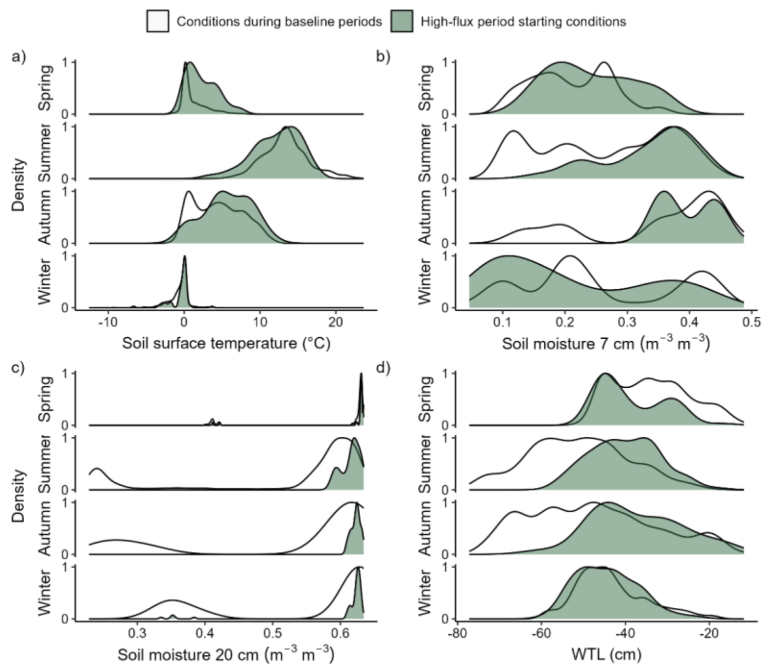

Conditions during baseline periods
High-flux period starting conditions
a)
b)
c)
d)
Density
Spring
Summer
Autumn
Winter
Soil surface temperature (°C)
Soil moisture 7 cm (m^{-3} m^{-3})
Soil moisture 20 cm (m^{-3} m^{-3})
WTL (cm)

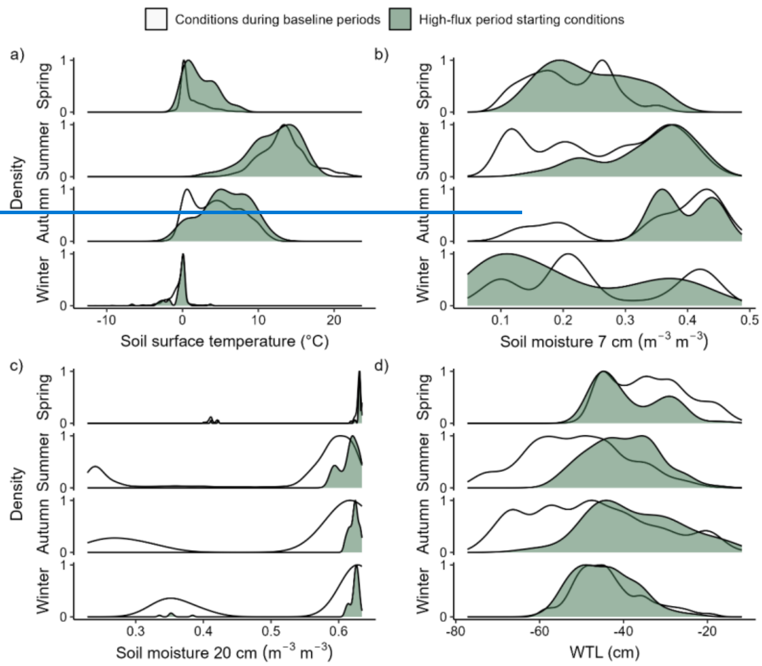

Figure 7: **High-flux period starting conditions in each season compared to conditions outside the high-flux periods. Density plots show the distribution ~~Seasonal density distributions~~ of high-flux periods starting on~~in~~ different (a) soil surface temperature~~temperatures~~, (b) soil moisture~~moistures~~, at 7 cm depth, (c) soil moisture~~moistures~~, at 20 cm depth, (d) and water table level~~levels~~, (WTL). The Y-axis shows scaled (0–1) proportion (%) of high-flux periods starting on conditions shown on the x-axis (1=most common high-flux periods starting condition, 0=no starting high-flux periods).~~Panels in each plot show density distribution for each thermal season.~~ For comparison, the variation in soil conditions during baseline periods is~~are~~ also shown (1=most common baseline period condition, 0=no such condition measured during baseline periods).~~.~~ All years and ~~high-flux periods of all~~ chambers are included. ~~Density distribution values on y-axis are scaled (0–1).~~**

3.4. Machine learning~~Modelling results~~

Soil moisture (both 7 and 20 cm), air temperature and WTL were considered to be the most important variables explaining the temporal variation of N_2O flux (Fig. 8) with the mean total variable importance (VI, 0 = no importance, 1 = high importance) being 0.7 and 0.6 for soil moisture (7 and 20 cm respectively) and 0.5 for air temperature and WTL. The mean VI of lags (1–7 days) for each environmental variable was the highest for 7 and 20 cm soil moisture (mean VI 0.3 for both) with 5 cm soil temperature and air temperature also having importance on lags (mean VI 0.25 and 0.20, respectively, Fig. S6). Lags of other variables received mean VIs lower than 0.1, but precipitation had an increasing VI towards the longest lags (6–7 days).

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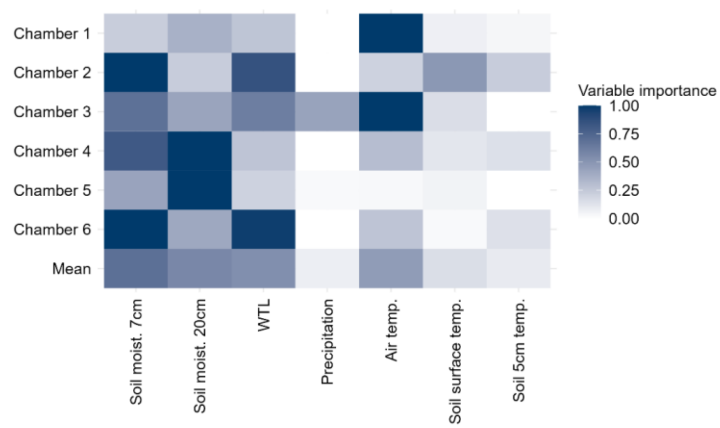

Figure 8: Total variable importance (VI)Unlagged soil moistures at 7 cm and 20 cm had mean variable importance (VI) scores 0.43 and 0.45 (respectively, 0 = lowest importance, 1 = highest importance) when VI scores were averaged across chambers (Fig. 8). Lagged (1–7 days) soil moisture variables received on average VI score of 0.31 (7 cm soil moisture) and 0.33 (20 cm soil moisture). The average VI score for unlagged air temperature was 0.45 and for soil surface temperature 0.24 and the variable importance generally decreased with increasing lag time. Unlagged soil temperature at 5 cm received VI score of an average 0.27 and increased VI scores also for lagged variables with the mean across lags 0.25. VI scores for WTL were on average 0.04 with little importance for lagged WTL in most chambers. Precipitation received VI score of 0.06 and increasing importance with increasing lag time. The most important variable and the importance of their individual lags varied between chambers with either soil moisture, WTL or air temperature receiving the highest VI score. High-flux chambers received high VI scores also for lagged temperature variables that were less important in low-flux chambers.

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Lag-specific VIs are presented in the supplements.

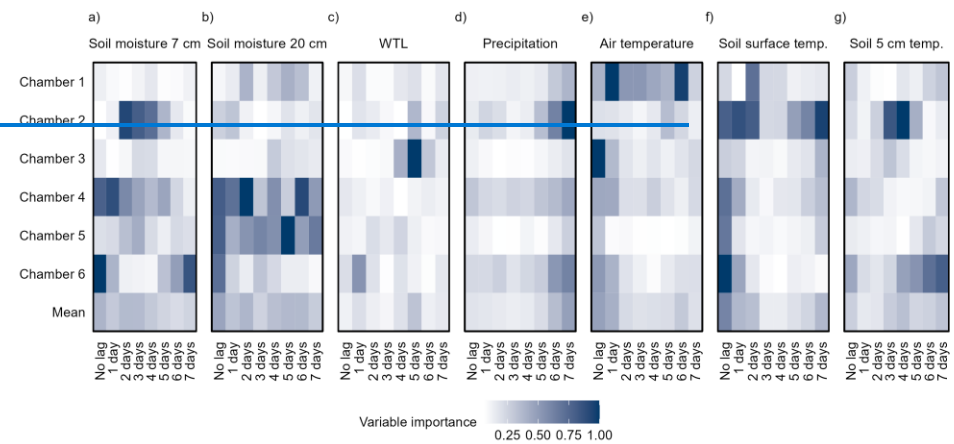

Figure 8: Variable importance (VI) scores, of different environmental variables in explaining the temporal variation of N_2O flux in random forest with conditional inference trees. Total VI is the sum of VIs of unlagged and lagged (1–7 days) and their lagged versions of the variable. Rows in the in explaining the temporal variation of N_2O. The matrix plot show VIsshows VI values separately for different chambers and(Chambers 1–6) as well as the mean VIsVI across all the chambers (Mean). VI values are means across 10 runs of Random forest with conditional inference trees. VI scores are scaled between 0 and 1 (0 = nolowest importance, 1 = highest importance) per chamber. Lag-specific VIs are shown in Fig. S6 to make VI scores comparable across chambers.

Accumulated local effects (ALE) curves for unlagged 7 cm soil moisture showed thatthe highest N_2O fluxes generally predicted on soil moisture values close to 0.3 m^{-3} m^{-3} or below 0.1 m^{-3} m^{-3} (Fig. 9 and S6). On moist conditions (> 0.3 m^{-3} m^{-3}), the highest fluxes were predicted for the 1–7 days lagged soil moisture when the soil was moist (> 0.35 m^{-3} m^{-3}). The lag. Predicted flux was typically the highest if soil moisture had been greater than 0.4 m^{-3} m^{-3} 3–7 days ago. On low 7 cm soil moistures (< 0.3 m^{-3} m^{-3}), the highest N_2O fluxes were predicted for unlagged soil moisture with the highest predicted flux varied from 1 to 7 dayslittle differences between chambers with a mean lag of 4 days. Predicted fluxes were also. On high when20 cm soil moisture (> 0.6 m^{-3} m^{-3}), predicted N_2O flux increased with increasing soil moisture in all chambers. Predicted flux on high 20 cm soil moisture was low (< 0.1 m^{-3} m^{-3}, frozen soil).the highest for lagged soil moisture only in two chambers. For WTL, the predicted flux was generally high the highest when WTL was high (> –45 cm), with the highest predicted flux on average for 4 days lagged WTL. The predicted flux for unlagged WTL was low at high WTL, while the predicted had been closer to the soil surface than –30 cm 3–7 days ago. The highest flux for unlagged WTL increased with decreasing WTL.was typically predicted for WTL deeper than –50 cm. In all chambers, N_2O flux was predicted to be the highest for 4–7 days afterlagged precipitation with an average lag of 5 days between chambers when daily precipitation had been at leastif rainfall had been about 5 mm or more.

For On temperatures above 5°C, the predicted N_2O fluxes increased with increasing air and soil surface temperatures above 5 °C, the predicted fluxes increased with increasing temperature, with the highest predicted fluxes at air temperatures abovetaking place when air and soil temperature exceeded 15 °C and soil temperatures above 10

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~~10~~ °C. For air and soil ~~, respectively. Below about 0–2 °C~~ temperatures (soil surface and 5 cm depth) below 0–2 °C, the predicted N_2O fluxes increased with decreasing ~~air, soil surface and soil 5 cm~~ temperature. In most chambers, the increase in ~~the~~ predicted flux for~~on~~ soil 5 cm temperature at 0–2 °C was particularly~~especially~~ strong. ~~with differences in the responses between immediate and lagged variables between chambers.~~ Responses between lagged and unlagged temperatures~~soil surface and air temperature variables also~~ varied among~~between~~ chambers.

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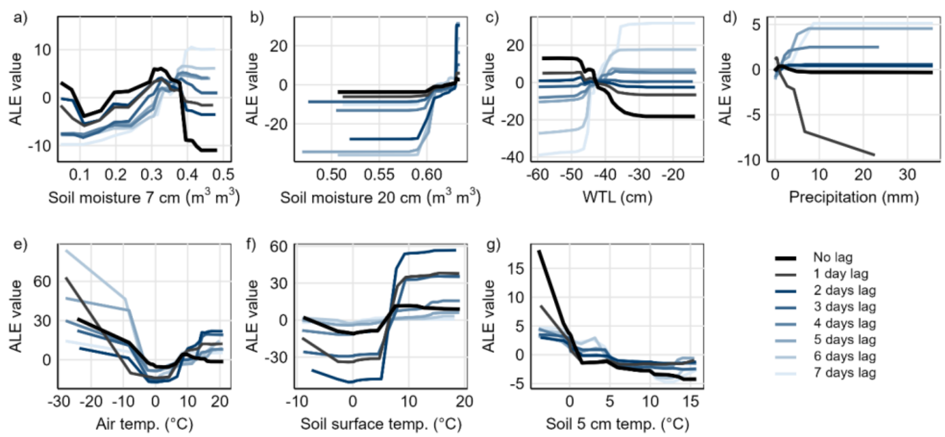


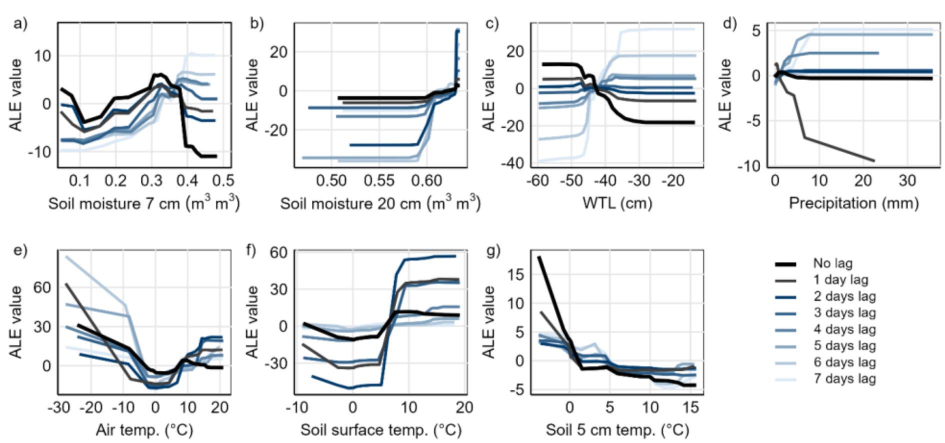
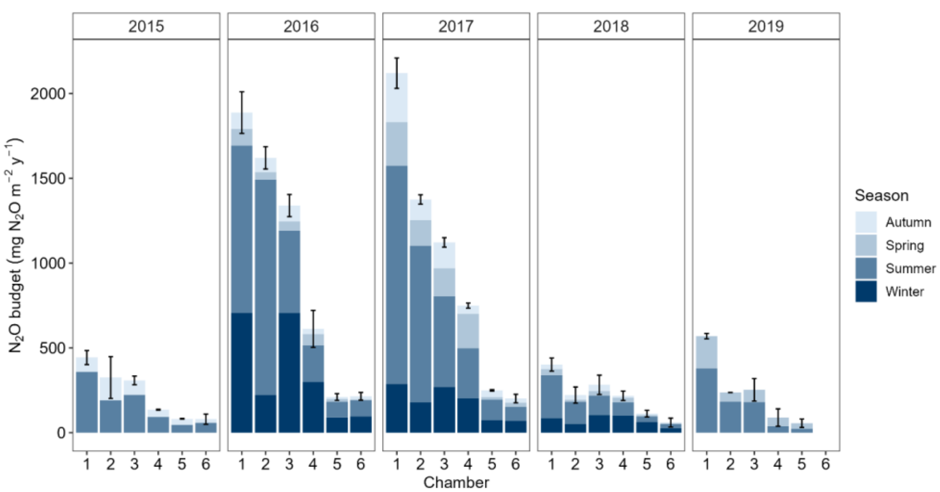


Figure 9: Response of predicted~~curves between~~ N_2O flux to different~~and~~ environmental conditions~~variables~~ for Chamber 1 visualized using Accumulated Local Effects (ALE). Figures illustrate how the predicted N_2O flux values deviate from the mean predicted flux (ALE = 0) along the gradients of (a) soil moisture at 7 cm depth, (b) soil moisture at 20 cm depth, (c) water table level (WTL), (d) precipitation, (e) air temperature, (f) soil surface temperature and (g) soil temperature at 5 cm. ALE responses for unlagged and lagged variables (1–7 days) are included. ~~Lines represent the mean ALE values of 10 model runs.~~ ALE responses for Chambers 2–6 are presented in supplements (S7~~S6~~).

3.5. N_2O budgets

The annual~~Annual~~ N_2O budgets of individual chambers varied between 60 (Chamber 6) and 2110 mg N_2O m^{-2} y^{-1} (Chamber 1) when considering the three full measurement years 2016, 2017 and 2018 (Fig. 10, Tables S8). In 2016 and 2017, annual~~S7). Annual,~~ N_2O budgets were 1120–2110~~higher than 1000~~ mg N_2O m^{-2} y^{-1} in the high-flux chambers and 200–740 mg N_2O m^{-2} y^{-1}~~(Chambers 1–3)~~ in the low-flux chambers. In 2018, the N_2O budgets were lower than 400~~2016 and 2017, but less than 500~~ mg N_2O m^{-2} y^{-1} in all chambers~~ in 2018~~. Winters and summers generally contributed~~ generally~~ the most to the annual N_2O budgets in all three years, with summers contributing on average 48 % and winters 34 % (Tables S8~~S7~~). The ~~seasonal~~ contributions of spring and autumn to the annual N_2O budgets were~~,~~ on average 10 % per season~~, 9 % for spring and autumn. Summer N_2O budgets in partially measured years 2015 and 2019 were smaller than in 2016 and 2017 but, especially in high-flux chambers, greater than in 2018~~.



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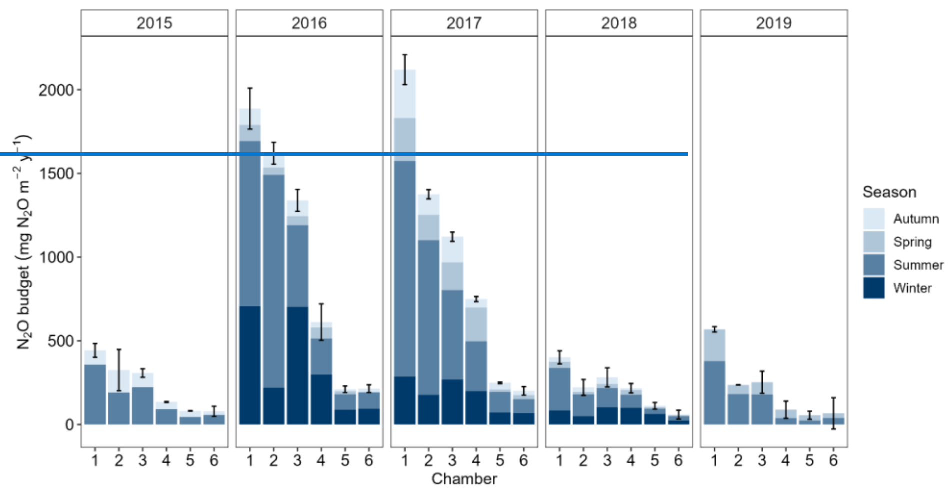

Figure 10: Annual N_2O budgets for each chamber and measurement year with seasonal contributions. Only seasons that were completely within the measurement period (4.5 years) are included. The N_2O budget for the year 2015 only includes summer and autumn, and the N_2O budget for the year 2019 only spring and summer. Measurements in Chamber 6 ended in early 2019 and no budget is shown for that year. Thermal seasons are used. Error bars denote total uncertainty related to the total N_2O budget of the year.

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4. Discussion

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4.1. Temporal variation of N_2O fluxes

The measured peatland forest N_2O fluxes were relatively high compared to N_2O fluxes reported forfrom most of the other boreal and temperate forests on peat andor mineral soils. The N_2O budgets of boreal peatland forests have mainly varied between -30 and 1200920 mg N_2O m^{-2} y^{-1} (Alm et al., 1999; Arnold et al., 2005; Minkkinen et al, 2020; Butlers et al., 2023), and in a similar range also in). The N_2O budgets of temperate mineral soil forests have varied within a similar range (Papen and Butterbach-Bahl, 1999; Luo et al., 2012). The N_2O budgets of our six automatic chambers are unlikely able to represent the N_2O budget ofWhile the whole site, but the mean annual N_2O budget of the chamber area greater than 950budgets in the present study were below 500 mg N_2O m^{-2} y^{-1} in 2018 in all measurement chambers, the annual N_2O budgets for three of the chambers exceeded 1000 mg N_2O m^{-2} y^{-1} in two full study years (2016 and 2017) out of three underlines the role of drained nutrient-rich peatland forest as hotspots for N_2O emissionsthe three full measurement years (Fig. 10). Similarly high or higher fluxes have been previously measured in peatland forest after clear-felling of the trees with especially logging residues linked with increased N_2O fluxes (Mäkiranta et al., 2012; Korkiakoski et al., 2019).

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Nutrient-rich peat with a relatively low C:N ratio likely explains the high N_2O budgets of the chamber area. study site. Low C:N ratio may have also have increased the sensitivity of the N_2O fluxfluxes to temporal variation in soil conditions (Klemedtsson et al., 2005; PihlatiePihlatie et al., 2010).; Hu et al., 2015). Although the selection harvest partial harvesting done at the site in the spring 2016 did not increase the N_2O budget of the harvested area compared

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to the control site according to Korkiakoski et al.~~.,~~ (2020), the effect of the harvest~~harvesting~~ on N_2O fluxes of individual chambers cannot be completely excluded. Since the N_2O budgets increased after harvesting in both the~~in~~ harvested ~~site~~ and ~~in~~ the control site (~~(see~~ Korkiakoski et al., 2020), most of the increase in N_2O budgets in the years 2016 and 2017 is likely explained by year-to-year variation in environmental conditions.

4.1. Seasonal variation of N_2O fluxes

Winters were characterized by N_2O flux peaks occurring during both freezing and thawing (Fig. 6, 7 and S5), similar to those reported in earlier studies (Teepe et al., 2001; Maljanen et al., 2007; Maljanen et al., 2010). Freezing-related N_2O emissions are likely explained by N_2O production in the remaining unfrozen water films that have increased C and N content in the freezing soil (Maljanen et al., 2007; Congreves et al., 2018). Winter N_2O flux peaks were measured when soil frost reached at least the 5 cm depth, whereas during winters with only shallow frost (< 5 cm, winters 2017–2018 and 2018–2019), high N_2O fluxes were less common. This indicates the importance of frost depth for winter N_2O emissions. The importance of ground frost severity and depth has also been suggested by others in several ecosystems (Nielsen et al., 2001; Koponen and Martikainen, 2004; Maljanen et al., 2007; Luo et al., 2012). The importance of deeper soil freezing may indicate that the freezing-related N_2O fluxes mainly originate from the freezing peat rather than from the surface litter layer, unlike suggested by Pihlatie et al. (2007) in a nutrient-poor peatland forest. Low C:N ratio may have favored N_2O production in the~~Considering~~ nutrient-rich peat (Klemedtsson et al., 2005). Site-specific differences in nutrient availability may influence the sensitivity of winter N_2O fluxes to frost depth.

Winters with deeper soil frost and higher N_2O emissions (winters 2015–2016 and 2016–2017) were characterized by discontinuous and shallow snow cover and variable temperature conditions (Fig. 3 and 4). Shallow snow cover combined with alternating cold and warm weather in the first two winters of the study period have likely increased the number of freeze-thaw cycles and their intensity leading to higher total N_2O fluxes (Maljanen et al., 2007; Ruan and Robertson, 2017). The results suggest the possibility for increasing winter N_2O emissions from drained peat soils if winters continue to warm, the occurrence of extreme temperature fluctuations increases and snow cover in the southern boreal region becomes shallower.

Similar to freezing, soil thawing triggered N_2O emissions during winter freeze-thaw cycles, but emissions ceased within a few days of the onset of the thawing phase even if soil temperature continued to rise (Fig. 6 and S5). Similar short-term N_2O peaks in response to soil thawing have been measured also in laboratory experiments by Teepe et al. (2001), and Koponen and Martikainen (2004). Thaw-related emissions have often been explained by increased N availability in the thawing soil (Groffman et al., 2006; Wagner-Riddle et al., 2017), and the cause of the short pulse of N_2O flux during winter thawing might be related to the rapid use of labile N made available during the soil freezing period. Release of N_2O accumulated in the frozen soil might also explain some of the short-term N_2O flux peaks during thaw (Maljanen et al., 2007; Pihlatie et al., 2010). The response of N_2O fluxes to soil thaw during winter was weaker than the response especially to early winter soil freezing which highlights the importance of freezing-related N_2O emissions in the studied ecosystem.

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soil and the tendency for high temporal variation of N_2O flux in several ecosystems (Maljanen et al., 2010; Luo et al., 2012; Molodovskaya et al., 2012; Anthony and Silver, 2021), the complex temporal dynamics of N_2O fluxes within and between years were expected. The high-flux period starting conditions and modelling results support previous evidence on the importance of freeze-thaw and dry-wet cycles strongly impacting temporal variation of N_2O fluxes (Butterbach-Bahl et al., 2013; Risk et al., 2013; Wagner-Riddle et al., 2017; Congreves et al., 2018). However, when comparing the temporal dynamics of N_2O flux with those previously published from boreal and temperate regions (Maljanen et al., 2010; Pihlatie et al., 2010; Luo et al., 2012; Molodovskaya et al., 2012; Anthony and Silver, 2021; Gerin et al., 2023), the present data underline the importance of summer and winter N_2O fluxes contributing to the annual N_2O budget more than fluxes in spring. Previously, several studies on both peat and mineral soils have emphasized the importance of thaw-related spring N_2O fluxes in the annual N_2O budgets, with pronounced spring N_2O fluxfluxes in the annual N_2O budget, with distinct spring N_2O peaks in some cases accounting for a large fraction of the annual budget (Pihlatie et al., 2010; Luo et al., 2012; Wang et al., 2023). In the present study, spring soil thaw triggered N_2O emissions, but emissions increased slowly with increasing soil temperature and peaked in late spring or summer, significantly later after soil thaw than reported in previous studies (Fig. 6 and S5). The strong temperature dependence of spring N_2O fluxes may indicate that the substrate for the spring N_2O production comes from the decomposing peat and litter in the warming soil. Temperature dependence of spring fluxes could be related to drained peat soil, where the major source of N is known to be decomposing peat (Martikainen et al., 1993). Different responses to thawing in winter compared to spring might be related to decreasing availability of N from early winter towards spring (Koponen and Martikainen, 2004; Congreves et al., 2018), which also likely explains the tendency for stronger response to freeze-thaw cycles in early winter. only moderately high N_2O flux peaks were measured in spring and early spring N_2O peaks were not typical. Year-to-year variation in N_2O budgets was more attributed to variation in winter and summer N_2O fluxes than variation in spring N_2O fluxes.

During winters with discontinuous and shallow snow cover combined with high temporal variation in air temperature below and above zero (2015–2016 and 2016–2017), the N_2O fluxes were higher compared to the snowier winters with more stable temperature conditions (2017–2018 and 2018–2019). The insulating properties of the thicker snowpack may have prevented the soil from freezing to deeper depth, decreasing N_2O fluxes during winter (Maljanen et al., 2009; Ruan and Robertson, 2017). Thicker snowpack combined with less variable air temperature conditions in the last two winters of the study period have likely decreased the number of freeze–thaw cycles and decreased intensity of them leading to smaller total N_2O flux during winter.

High-flux periods during the growing season, especially in the summer,during summers were associatedlinked with precipitation events that increased soil moisture and raised WTL (Fig. 6, 7 and S5).WTL. These high-flux periodsevents increased the total N_2O budget of the rainy summers (2016 and 2017), whereas thewhile N_2O budget in dry summer (2018) was low in the warm and dry summer 2018.. Precipitation events may have increased the number of anoxic microsites in the soil, favoring N_2O production also through denitrification (Congreves et al., 2018). Fast2019; Song et al., 2022). Active peat decomposition in the warm soil during the summer has likely reducedalso decreased oxygen availability in the soil and increased N availability from the mineralizing peat resulting inleading to high N_2O fluxesemissions after summer rain events (Maljanen et al., 2003). Low surface soil moisture

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has likely limited N$_2$O fluxesproduction during drought, leading to small N$_2$O budgets in dry summer are likely explained by low microbial activity and substrate availability in the dry soil (Borken and Matzner, 2009; Congreves et al., 2018). Our results on summer and winter N$_2$O fluxes suggest that low N$_2$O fluxes during dry summers might offset the effect of the increasing winter N$_2$O fluxes on annual N$_2$O budgets if dry summers become more frequent in the warming climate.2018; Harry et al., 2021).

N$_2$O fluxes duringAutumn and spring N$_2$O fluxes varied relatively little between years with different weather conditions, indicating weaker sensitivity of spring and autumn were low and showed little year-N$_2$O fluxes to-year variability (Fig. 5, 6 and S5). Low seasonal weather conditions. N$_2$O fluxes during autumn N$_2$O emissions have been low also been measured in part of the previous studies (Maljanen et al., 2003; Luo et al., 2012), althoughbut Pihlatie et al. (2007)(2007) and Alm et al. (1999) found increased autumn N$_2$O fluxes after litter fall in drained peatland forests. The low contribution of autumn N$_2$O fluxes to annual emissions in the present study is probably explained by the more nutrient-rich peat and the lower importance of N$_2$O production in the litter layer in the total N$_2$O production (Martikainen et al., 1993; Pihlatie et al., 2007). The results indicate that the site-specific differences in the peat nutrient availability forest sites. Site-specific differences could alter the contributions of different seasons to annual N$_2$O budgets. High temporal variability of fluxes and greater sensitivity of N$_2$O fluxes to environmental conditions in nutrient-rich peatland forests are likely to increase the and affect sensitivity of N$_2$O budgets to increasing variability in seasonaldiffering conditions in different seasons.

As the changingclimate changes, the typical weather conditions for each season are predicted to change. In northern latitudes, winters are expected to become warmer and wetter, and summer droughts are expected to become more frequent (Zhao and Dai, 2017; IPCC, 2021). The high year-to-year variability in N$_2$O fluxes, which was largely attributed to variation in summer and winter weather conditions, may imply changes and increased variability in annual N$_2$O budgets if weather patterns of these seasons change and the frequency of extreme weather events increases due to climate change.

4.2. Linkages to spatial variation

LowerCapturing temporal patterns of N$_2$O fluxes from the three low-fluxsix chambers (maximum flux < 400 µg N$_2$O m^{-2} h^{-1}) allowed us to explore the linkages between the spatial and temporal patterns of N$_2$O fluxes across different measurement years. Lower N$_2$O fluxes from three of the chambers compared to high N$_2$O fluxes (maximum flux > 1100 µg N$_2$O m^{-2} h^{-1}) measured in the other three high-flux chambers demonstrate the often spatially variable nature of N$_2$O flux even on a small scale within a few tens of meters (Groffman et al., 2009; Hénault et al., 2012; Jungkunst et al., 2012).

What was notable was that the spatial differences in N$_2$O fluxes between chambers were persistent across years. different years. The mean and the maximum daily mean fluxes were consistently larger for the high flux chambers (Chambers 1–3), although differences between chambers were smaller during the low flux year 2018 due to a larger decrease in N$_2$O fluxes in high-flux chambers compared to low-flux chambers. Despite large temporal variations in flux within and between years, the spatial patterns of N$_2$O flux remained throughout the measurement period.

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The persistence of spatial variation implies that spatial variation of N_2O flux is controlled by long-term controls that persist throughout years with different weather conditions. The long-term controls could include, for example, spatial variation in soil properties (e.g. pH, porosity, C and N content) or placement of plant roots that have both been suggested to affect the spatial variation of N_2O fluxes even on a very small scale within the soil (Butterbach-Bahl et al., 2002; Jungkunst et al., 2012; Kuzyakov and Blagodatskaya, 2015). However, it must be noted that results regarding the causes of within-site spatial variation have been highly variable between different studies, and few studies have managed to explain spatial variation well (Ball et al., 2000; Butterbach-Bahl et al., 2002; Yanai et al., 2003; Giles et al., 2012; Jungkunst et al., 2012). The linkages between soil properties, vegetation and N_2O fluxes are complex, with interactions making the relations between the N_2O flux and soil system difficult to understand.

The long-term controls could include, for example, spatial variation in soil properties (e.g. pH, bulk density, availability of different forms of N) or placement of plant roots both of which have been suggested to influence the spatial variation in N_2O fluxes even at very small scales within the soil (Butterbach-Bahl et al., 2002; Jungkunst et al., 2012; Kuzyakov and Blagodatskaya, 2015). In the present study, the high-flux chambers had fewer trees nearbynear them than low-flux chambers, and the distance to nearby trees was greater (Fig. 1, Table S1). Tree rootsshorter in low-flux chambers (Fig. 1, Table S1). This could indicate the importance of trees shaping the spatial patterns of peatland forest floor N_2O fluxes, similar as suggested by Butterbach-Bahl et al. (2002) in mineral soil forest. Trees may have affectedimpacted the availability of different forms of nitrogen through nitrogen uptake and nitrogen inputs to soil above and below ground (Kaiser et al., 2011; Kuzyakov and Blagodatskaya, 2015; Hu et al., 2016), resulting in higher fluxes further away from the trees in this case. Because). Since trees also affect the forest floor microclimate, ground vegetation and soil conditions throughby shading and affecting transpiration and by influencing the distribution of rainfall and lightrain fall in the forest (Butterbach-Bahl et al., 2002; Aalto et al., 2022), variation in the tree cover may alsocould have contributed to the spatio-temporal dynamics of peatland forest N_2O fluxes.

Although the distance to trees seemed to explain somechambers had persistently different levels of the spatial variation in N_2O flux, throughout the study period, the chambers had clear similarities in the temporal dynamics of the N_2O flux (Fig. 4). High-flux and baseline flux periods identified for each chamber occurred often at the spatial variationsame time. N_2O flux time series, especially within the small and among high-flux and small flux chamber groups, remained unexplained. Ground vegetation was also not linked to spatial variation of N_2O. The results emphasize the importance of comprehensive soil sampling (e.g. N forms, bulk density, pH, C:N, root density) and chamber-specific measurements of environmental variables (e.g. soil moisture, soil temperature, WTL), when studying spatio-temporal variation of N_2O flux, especially in the forested study sitescorrelated, implying shared temporal patterns but stronger similarities between chambers with variable microclimate.

Despite the large spatial variation in the N_2O flux, the high-flux periods identified for each chamber typically occurred at similar times, although the exact length and timing of the high-flux periods varied (Fig. 4, Table S4).a more similar flux level. Similarities in the temporal variation of fluxes suggest that temporalflux patterns between the chambers indicate that the changes in the soil environmental conditions affectedaffect N_2O fluxes relatively similarly across space. In previousdespite the large spatial variation in flux.

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Previous studies, temporal using manual chambers in agricultural settings with more variable soil conditions have found partly opposing results. Temporal patterns within sites werehave been either variable or commonshared across space (Velthof et al., 2000; Krichels and Yang,et al., 2019), with both findings mainly attributed to the spatio-temporal variation of soil moisture. Stronger similarities in the temporal variation of N_2O flux within the low and high-flux chamber groups indicate that some differences in the response of N_2O flux to environmental conditions conditions. Soil moisture data from the individual chambers were not available here, but the chambers seemingly reached soil conditions triggering N_2O production at similar times, although the resulting N_2O flux level varied between chambers. In the presence of more topographical variation as in the study by Krichels et al. (2019), spatial variation in soil conditions could have led to more variable temporal patterns in N_2O flux across space if triggering conditions of N_2O production were reached at different times in different parts of the area. In the present study area, the factors causing the high and temporally persistent spatial variation in flux have not affected the way fluxes respond to temporal variation in soil conditions leading to similarities in temporal dynamics of the flux.

Differences in the temporal patterns between the high-flux and low-flux chambers were mainly related to the length and relative height of the high-flux periods as well as to the exact timing of the peak top within the high-flux periods. This has likely decreased the correlation of the temporal flux patterns between high-flux chambers and low-flux chambers. Since soil temperature variables were able to explain differences in temporal patterns of N2O flux between most chamber pairs, N_2O peak length, timing, and relative height of flux peaks could be further shaped by spatial differences in the magnitude by which N_2O fluxes respond to temperature conditions.

4.3. Freeze-thaw cycles

Increased winter N_2O fluxes occurred in different phases of freeze-thaw cycles; during the onset of freezing periods, during repeated freeze-thaw events in the middle of the winter and during or after thawing in late winter and spring. Increased N_2O fluxes in different phases of freeze-thaw periods can be seen, for example, in winter 2016–2017 (Fig. 6), with increased N_2O fluxes measured during the early winter freezing as well as during and after part of the short freezing periods later in winter and spring.

Previous results about the timing of increased N_2O fluxes regarding freeze-thaw cycles have been variable. Some studies report increased N_2O fluxes during the freezing period (Papen and Butterbach-Bahl, 1999; Teepe et al., 2001; Maljanen et al., 2009, 2010; Ruan and Roberston, 2017), while part of the studies report high fluxes mainly during and after the thawing (Koponen and Martikainen, 2004; Pihlatie et al., 2010; Luo et al., 2012; Molodovskaya et al., 2012). Although here, the spring thaw resulted in a steady increase in N_2O flux, with peak N_2O flux reached later in spring or early summer, short-term N_2O flux peak during soil melting was not observed. High variability in the temporal patterns of winter and spring N_2O flux in different studies highlights the need to understand the causes of site-specific differences that create variable winter N_2O flux patterns.

The highest winter N_2O fluxes typically occurred in the early winter soon after the soil freezing at the time when frost reached 5 cm depth (Fig. 6 and 7, S5). Winter high-flux periods with peak N_2O fluxes clearly elevated from the baseline flux level were generally only measured during winters when soil frost reached 5 cm depth several times (winters 2015–2016 and 2016–2017) and only during freeze-thaw cycles occurring at 5 cm depth (late winter

~~2016–2017). The importance of deeper soil freezing rather than freezing only of the soil surface may indicate that the winter N_2O fluxes during freezing~~ may be related to the overall spatial variation of the flux~~have originated from the freezing peat rather than from the freezing litter at the surface of the soil. The importance of the severity of ground frost and frost depth affecting N_2O fluxes has also been suggested by others (Nielsen et al., 2001; Koponen and Martikainen, 2004; Luo et al., 2012). The conclusion about the possible source of winter N_2O fluxes in the topsoil peat rather than in the soil surface litter differs from the results of Pihlatie et al. (2010) in a nutrient-poor peatland forest site. More nutrient-rich peat with a low C:N ratio may have favored N_2O production in peat (Regina et al., 1998; Ojanen et al., 2010). Higher nitrogen availability in peat may have enabled a stronger link between winter N_2O fluxes and conditions experienced in the peat. Site-specific differences in nutrient availability in different parts of the soil may affect the sensitivity of winter N_2O fluxes to frost depth~~.

4.3~~4~~ Delayed responses ~~and interactions~~

The results ~~of this study~~ indicate that N_2O flux has a delayed response to precipitation events with peak N_2O fluxes measured on average 4 days after~~general importance of lagged~~ soil moisture and WTL peaks, and 5 ~~conditions affecting N_2O fluxes on the short time scale of 1–7 days. Peak N_2O fluxes were reached sometimes several~~ days after rainfall (Fig. ~~the highest surface soil moisture and WTL values were measured (Fig.~~ 9 and S7~~, S6~~). Studies mostly conducted on~~from~~ mineral soils in laboratories have found short time~~no~~ lags from the onset of anaerobiosis or water saturation to the highest measured N_2O production, with ~~or~~ lags ranging from~~of a~~ few hours to less than ~~between the soil moisture peak and the highest N_2O fluxes, while others have found lags of a maximum of~~ two days (Firestone and Tiedje, 1979; Smith and Tiedje, 1979~~Firestone and Tiedje, 1979; Smith and Tiedje, 1979~~; Russow et al., 2000; Song et al., 2019). Compared to the previous studies, the observed~~Song et al., 2022). In this study, the~~ lag times are long, with indication~~time between surface soil moisture peak and the peak N_2O fluxes was typically at least two days, with indications~~ for even longer lags than seven days in some chambers.

The present data only allow us to hypothesize the causes of the long lag times after precipitation events. The ~~Long delays between the soil moisture peak and peak N_2O fluxes may be due to the~~ ability of peat to retain moisture and thus ~~therefore retain~~ anaerobic microsites in the soil means that anaerobic conditions ~~soil~~ for denitrification are maintained and the possible co-occurrence of nitrification and denitrification can last for ~~a~~ longer than in~~time compared to~~ most mineral soils (Päivänen, 1973; Wrage et al., 2001; Walczak et al., 2002). The highest N_2O fluxes during the growing season were reached on intermediate soil moisture (0.3–0.4 m^{-3} m^{-3}) after the soil had started to drain and WTL had started to decrease after a precipitation event (Fig. 7 and 9, S7). Based on this study and previous laboratory studies, we suggest that after a period of high N_2O reduction activity and therefore relatively low N_2O fluxes from denitrification in the wet soil soon after rain, N_2O production in the draining soil increased (Firestone and Tiedje, 1979; Russow et al., 2000; Congreves et al., 2018). As soil continued to drain, conditions for simultaneous nitrification and denitrification became optimal (Bateman and Baggs, 2005; Wang et al., 2021; Song et al., 2022), further increasing N_2O production and leading to the peak N_2O flux some days after rain. The ability of peat to retain moisture could extend the time for soil drainage after rainfall and thus time before optimal conditions for N_2O production are reached. Hydrophobic properties of dry peat soils can also extend the time before N_2O fluxes respond

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Commented [HR54]: Lags related to soil moisture are now discussed more carefully and uncertainties related to soil moisture data are brought up more. WTL and precipitation strengthens the discussion related to soil moisture more than previously.

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Commented [HR55]: Explanation about the linkage between peat soil properties and long lag-times is now explained better and more clearly.

to soil wetting (Borken and Matzner, 2009) contributing to longer lag times. To determine exact lag times in response to soil moisture peaks, chamber-specific soil moisture data would be required.

Differences in the importance of different variables and their lags between chambers may indicate varying lag times and sensitivities to different soil moisture and WTL conditions across space. Despite spatial differences in lag times and differences in the most important variables for which the lags were identified, the highest N_2O fluxes on unfrozen soil were reached on intermediate soil moistures (0.3–0.4 m^{-3} m^{-3}) after the soil had started to drain and WTL started to decrease after a precipitation event. The optimal conditions for high N_2O fluxes on intermediate soil moistures could be explained by the simultaneous occurrence of oxic and anoxic soil microsites that allow simultaneous nitrification and denitrification in draining soil (Bateman and Baggs, 2005; Wang et al., 2021; Song et al., 2022).

Although models were not run forto different seasons separately, the response of N_2O fluxes to precipitation events seemed to be soil moisture peaks was slower duringin autumn and resulted in lower. Lag times between peak N_2O fluxes and soil moisture peak increased and the height of the N_2O flux peaks (Fig. 6 and S5). decreased from summer towards late autumn. Lower temperatures in autumn likelyleading to decreased microbial activity and mineralizationdecreasing availability of N from decomposing peat, which could in colder soil may explain lower fluxes and slowerslow response of N_2O fluxes to precipitation eventssoil moisture peaks in autumn (Holtan-Hartwig et al., 2002). Chamber differences in the lag times associated with precipitation events and differences in the variable importance of different environmental variables (Fig. 8 and S6) may also indicate varying sensitivities of N_2O production to spatially varying soil conditions. These differences may be related to different microbial community, substrate availability or soil properties that have been identified as important controls of N_2O production (Hénault et al., 2012; Butterbach-Bahl et al., 2013; Hu et al., 2015) and are likely to shape the response of N_2O production to environmental conditionsThe finding reminds us of the importance of interactions affecting seasonal patterns of N_2O fluxes.

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5. Conclusions

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ThisThe study shows extremely high temporal and spatial variability in peatland forest N_2O fluxes with persistent spatial patterns across years with different environmental conditions.and common temporal dynamics across space. The considerable small-scale spatial variation in N_2O fluxes was persistent in time and is therefore likely to be influenced by relatively long-term controls in the soil. The temporal variation of N_2O flux was instead strongly influenced by seasonal weather conditions, especially such as precipitation, snow depth and drought. Temporally varying soil environmental conditions affect N_2O fluxes through complex responses that include delayed responses to soil wetting. Interactions between spatially and temporally varying soil conditions, such as and interactions, leading to high temporal variation in N_2O flux between years as well as within and between seasons. Responses of N_2O fluxes to environmental conditions include time lags that further shape temporal patterns of N_2O fluxes.

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The observed high peatland forest N_2O emissions highlight the role of N_2O emissions originating from non-agricultural systems and the importance of considering the spatio-temporal dynamics of highly seasonally variable N_2O fluxes, especially in boreal regions with strong seasonal patterns. The results indicate high importance of summer

~~precipitation and winter~~ temperature, further shape the spatio-temporal patterns of N_2O flux. The considerable small-scale spatial variation in N_2O fluxes is likely to be influenced by relatively long-term controls such as soil properties and positioning of trees ~~and snow conditions for seasonal and annual N_2O budgets, and thus the possibility of increased annual variability in N_2O emissions as seasonal weather conditions change in a warming climate~~.

The observed high N_2O fluxes from the peatland forest highlight the role of nutrient-rich drained peat soils as hotspots for N_2O emissions in the boreal region. The dependence of N_2O budgets on seasonally varying weather conditions suggests high sensitivity of peatland forest N_2O budgets to changing climate. Winter N_2O emissions will likely increase in the future due to warming winters with shallow and discontinuous snow cover. Summer N_2O emissions may decrease and possibly offset the effect of warming winters on annual N_2O budgets in dry years. Year-to-year variation in N_2O emissions will likely increase as extreme weather events are predicted to become more frequent.

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6. Appendices

Appendix A. Thermal seasons

Thermal winter was the season with daily mean air temperatures persistently below 0 °C and thermal summer ~~a~~ season with daily mean air temperatures persistently above 10 °C (Ruosteenoja et al., 2016~~2011~~; Finnish Meteorological Institute, 2023). During spring and autumn, temperatures varied between 0–10 °C. Cumulative temperature sums of daily mean temperatures were then used to identify the starting days of the thermal seasons at which temperature went~~goes~~ persistently above or below the seasonal temperature threshold (0 or 10 °C).~~,~~ The starting day of the thermal winter was the day after the annual cumulative temperature sum reached the maximum. The starting day of the thermal spring was the day after the minimum cumulative temperature sum was reached. Starting days of thermal summer and autumn were calculated similarly but by extracting 10 °C from the air temperatures before calculating the cumulative temperature sum (modified temperature sum). The day after the minimum modified temperature sum was reached was defined as the starting date of the summer, while the maximum modified cumulative temperature pointed the onset of thermal autumn.

Appendix B. Evaluating the model performance

R_2 of the chamber-specific models used in the analyses varied between 0.72 and 0.85 in OOB data, and between 0.60 and 0.69 in training period evaluation data (30 % of training period data) (Table B1). When predicting N_2O fluxes outside the training period (fourth measurement year), R_2 varied between 0.02 and 0.69. The performance~~Performance~~ of ~~N_2O~~ gap-filling models was tested only using OOB data and evaluation data within the whole study~~measurement~~ period (30 % of data). For gap-filling models, R_2 in OOB data varied between 0.71 and 0.84, while R_2 in evaluation data varied between 0.67 and 0.78 (Table B2).

For the models used in the analysis, the poor prediction accuracy outside of the training period, especially in Chambers~~chambers~~ 3, 4, and 6, was likely due to overestimation of the general flux level during the relatively dry year 2019, which was excluded from the training period (Fig. S9). ~~S8).~~The model was also unable to predict anomalous high-flux period in low-flux winter 2018–2019 in Chamber 5 likely due to a lack of chamber-specific soil temperature data deeper in the soil. The temporal patterns of the flux otherwise followed temporal patterns of measured fluxes relatively well. Poor prediction accuracy outside the training period in part of the chambers indicates that predicting N_2O fluxes to a year with distinct environmental conditions compared to the years in the training data may lead to large under or overestimation of N_2O fluxes. The used models could benefit from additional explanatory variables, such as redox potential or the availability of different forms of nitrogen (Rubol et al., 2012; Saha et al., 2020). Including additional soil variables in the model could decrease the need to have excessively large model training periods to accurately predict and gap-fill N_2O fluxes.

Table B1: Model performance in evaluation datasets. Out-~~-~~of-~~-~~bag (OOB) data refers to data left outside model training in random~~Random~~ forest with conditional inference trees, evaluation data within the training period refers to 30 % of data randomly left aside for model evaluation and evaluation data outside the training period refers to the fourth measurement year outside model training period. ~~(3 years).~~

Chamber	Evaluation data	RMSE	R^2
1	OOB	138.8	0.75
	Within training period	134.9	0.60
	Outside training period	113.7	0.67
2	OOB	105.7	0.84
	Within training period	106.0	0.69
	Outside training period	85.1	0.69
3	OOB	81.0	0.72
	Within training period	93.7	0.64
	Outside training period	75.7	0.02
4	OOB	36.3	0.83
	Within training period	29.5	0.77
	Outside training period	56.6	0.01
5	OOB	14.5	0.85
	Within training period	12.7	0.65
	Outside training period	22.0	0.33
6	OOB	10.2	0.85
	Within training period	10.3	0.68
	Outside training period	17.0	0.03

Table B2: Performance of gap-filling models on evaluation datasets. Out-~~-~~of-~~-~~bag (OOB) data refers to data left outside model training in random~~Random~~ forest with conditional inference trees and evaluation data within the training period refers to 30 % of training period data that was randomly left aside for model evaluation. The training~~Training~~ period of gap-filling models covers the total study~~measurement~~ period (4.5 years).

Chamber	Evaluation data	RMSE	R^2
1	OOB	118.3	0.80
	Within training period	124.7	0.67
2	OOB	90.2	0.84
	Within training period	86.6	0.78
3	OOB	80.7	0.74
	Within training period	62.1	0.69
4	OOB	30.3	0.83
	Within training period	28.6	0.76
5	OOB	16.7	0.71
	Within training period	14.0	0.71
6	OOB	9.9	0.82
	Within training period	9.7	0.72

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7. Data availability

Flux data and supporting environmental data are available at: https://doi.org/10.5281/zenodo.8142188 (Rautakoski et al., 2023a). Simplified R code of the machine learning part of the study is made freely available at: https://github.com/helenemilii/N2O_modeling. ~~R codes used in data analysis are available from the corresponding author by request.~~ Python codes used in flux calculation and R codes used in data analysis are available from the corresponding author by request.

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8. Supplement

The supplement of the article is available at: https://doi.org/10.5281/zenodo.10533480 (Rautakoski et al., 2023b).

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9. Author Contributions

AL, MA, MK and PO set up the study design. Field maintenance of measurement systems was carried out by MK, AL and PO. Fluxes were calculated by MK and filtered by HR. Data analysis, modeling and writing of the article were done~~modelling was carried out~~ by HR with the support of AL and other ~~JM. HR wrote the article with the help of~~ co-authors.

10. Competing interests

The authors declare that they have no conflict of interest.

11. Acknowledgments

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