



Vegetation, drainage and peat depth control ecosystem scale nitrogen loading from a cultivated peatland

Miika Läpikivi^{1,2}, Maarit Liimatainen^{1,2}, Milla Niiranen¹, Valtteri Hyöky², Hermann Aaltonen³, Bjørn Kløve², Hannu Marttila²

5 ¹ Natural Resources Institute Finland, Production Systems, Paavo Havaksen tie 3, FI-90570 Oulu, Finland

² University of Oulu, Water, Energy and Environmental Engineering Research Unit, Pentti Kaiteran katu 1, FI-90570 Oulu, Finland

³ Finnish Meteorological Institute, Climate System Research, Erik Palménin aukio 1, FI-00560 Helsinki, Finland

Correspondence to: Miika Läpikivi (miika.lapikivi@luke.fi)

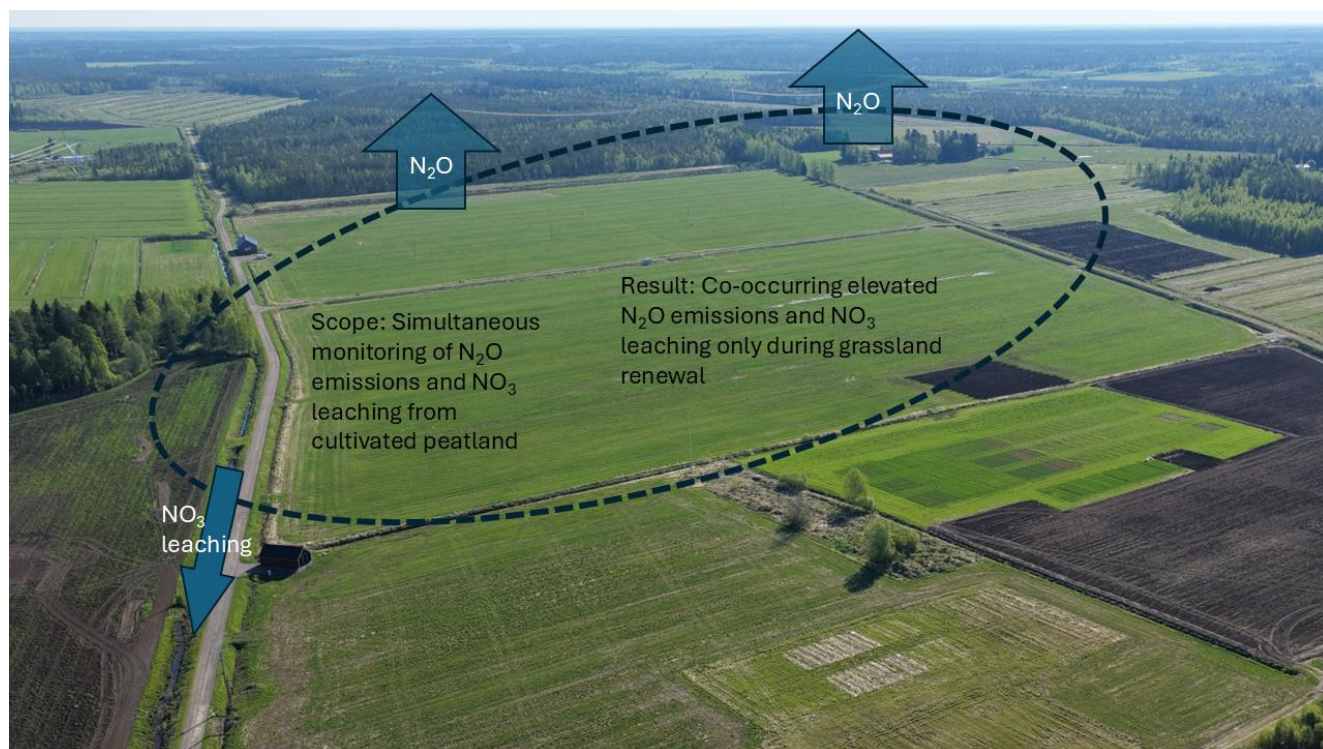
10 **Abstract.** Organic soils are productive for cultivation, but leaching loss to water bodies and the atmosphere emissions causes high environmental and climatic costs. Nutrient losses are not constant in time or space; instead, they are formed by the interplay between soil stocks, farmer management actions, hydrological processes, and weather drivers. Monitoring systems that capture these aspects are necessary to better integrate cultivated peatlands into broader hydrological and climate systems and assess the effectiveness of farm-level interventions to mitigate harmful emissions.

15 We conducted a two-year study with hourly monitoring of the water table depth, drain discharge, drainage nitrate (NO₃), and atmospheric nitrous oxide (N₂O) concentrations in a 26-ha cultivated peatland on top of an acid sulfate affected subsoil. The field was divided into six blocks with an organic horizon varying from 15 to 75 cm. During the monitoring period, the grass sward was renewed and the drainage depth was adjusted from 80 to 30 cm.

20 Drainage flow and NO₃-N concentrations showed high seasonal variability, with the highest drainage flow occurring together with a high NO₃-N concentration and an elevated water table during spring and autumn, and the lowest concentration and drain discharge during the growing season. Adjustment of the drainage depth drastically reduced the generation of drain discharge; however, the drainage NO₃-N concentration was only slightly reduced. Annual export of NO₃-N through drainage systems from deep and shallow peat portions was 4.75 kg NO₃-N h⁻¹ year⁻¹ and 3.81 kg NO₃-N h⁻¹ year⁻¹ with majority of NO₃-N leaching occurring during single spring melt event during period with bare soil without plant cover.

25 Atmospheric N₂O concentrations co-varied with drainage NO₃-N only during bare soil periods when elevated soil temperatures coincided with high NO₃ availability. During vegetated periods, this coupling was absent despite similar NO₃ levels, highlighting the critical role of plant uptake and environmental constraints in regulating N₂O emissions.

30 In addition to process insights, this study demonstrates the feasibility and limitations of high-frequency optical NO₃-monitoring in iron-rich, organic drainage waters. Together, the results highlight the importance of hydrological event timing, vegetation cover, and drainage management in controlling nitrogen losses and provide guidance for both mitigation strategies and monitoring system design in peatland and agricultural ecosystems.





1 Introduction

Peatlands are major terrestrial stores of carbon (C) and nitrogen (N) (Leifeld and Menichetti, 2018); however, their drainage for agriculture fundamentally alters these reservoirs and accelerates their losses to the atmosphere and aquatic systems (Freeman et al., 2022; Silverthorn et al., 2026). While preventing new drainage and promoting rewetting are effective strategies to reduce C and N losses, large areas of peatlands remain under agricultural use owing to economic and food security pressures. Various management methods for drained peat soils, such as reduced drainage depth (Freeman et al., 2022), conversion to grassland (Holzknecht et al., 2025), abandonment (Keck et al., 2024), or reduced tillage (Honkanen et al., 2024) are suggested to optimise growing or minimise climate change impacts, but clear evidence of their efficacy is still lacking.

Managed grassland for feed production to ruminants is a common land use for European agriculture, especially in Northern Europe, where climatic conditions favour perennial forage production (Olesen and Bindi, 2002). A typical rotation on intensively managed grassland consists of 3-4 years of continuous grass cover, which is harvested and fertilised 1-3 times during the summer. After that, the grass sward is terminated with herbicide, fields are ploughed, and fields are sown with cereal crops for one year before starting the new grass sward (Virkajärvi et al., 2015).

Nitrogen-based leaching to water bodies, such as nitrate (NO_3^-), and emissions to the atmosphere as nitrous oxide (N_2O), are major components of the negative environmental impacts of drained cultivated peatlands (Gerin et al., 2023; Pham et al., 2023). Mineralisation of soil organic matter to ammonium (NH_4^+) and nitrification to water soluble nitrate (NO_3^-) is a major source of harmful leaching (Frick et al., 2022), which can be denitrified to N_2O (Butterbach-Bahl et al., 2013) or mobilised through drainage systems when hydrological connections are activated in the soil profile (Cain et al., 2022).

Grassland renewal has been identified as a hotspot for N_2O emissions and NO_3^- leaching owing to the enhanced decomposition of organic matter together with reduced nitrogen uptake by vegetation (Offermanns et al., 2023; Semberg et al., 2026). Previously, the availability of dissolved NO_3^- in pore water or soil has been linked to higher N_2O fluxes (Buchen et al., 2017; Offermanns et al., 2023; Velthof et al., 2010), suggesting that hydrological and gaseous nitrogen loss pathways may be closely interconnected. Despite this, high-frequency continuous observations of NO_3^- leaching remain limited in the context of field-scale drained peatland production systems. An improved understanding of the temporal coupling of nitrogen loss pathways can help develop effective mitigation strategies and improve process-based models.

Here, we employed simultaneous high-frequency monitoring of drain runoff NO_3^- and atmospheric N_2O concentrations for two years on a northern cultivated peatland during grass renewal and under different water table management periods. This study has three aims. First, we assessed the long-term performance of a UV spectrometric nitrate sensor in iron and organic compound-rich subsurface drainage operated via a multiplexed sampler. Second, we quantified how a rising drainage outlet affects the generation of NO_3^- leaching across drainage blocks, highlighting the implications for the timing and magnitude of nitrate export. Third, we evaluated the conditions under which drainage NO_3^- concentration co-vary with elevated



70 atmospheric N₂O concentration. Collectively, these objectives deliver both an operational blueprint for high-frequency optical monitoring in challenging peat systems and process insights necessary for effective mitigation and modelling of nitrogen losses in cultivated peatlands.

75 This paper utilized field-scale measurements of greenhouse gases and nutrients in drainage water. Nitrogen losses through the drainage were highly seasonal, are affected by the drainage management and the peat depth within the field. Increased greenhouse gas concentrations were observed with increased concentration in drainage water was observed only during the grassland renewal. The results show that management actions can have meaningful impact to mitigate impacts of managed peatlands.

2. Materials and Methods

80 2.1 Study site and field management

Monitoring is located at the NorPeat facility (Lat 64.684°, Lon 25.106°), a 26-ha cultivated peatland located in the Finnish west coast lowlands. The organic soil horizon in the field varied from 16 to 76 cm. Three of the blocks (1, 2, and 4) had an average peat depth of 56 cm. Blocks 3, 5, and 6 had relatively shallow organic horizons of 34 cm. The subsoil consists of fine-grained mineral soils and is affected by acid sulfate deposits (Yli-Halla et al., 2022). This open-air facility is part of the
85 AnaEE network (AnaEE-ERIC, 2026). The climatological normal (1991-2020) annual average temperature is 3.2 °C and annual precipitation is 555 mm. The snow-covered period begins in November and continues until April (Jokinen et al., 2021). During the study period, the fields were used in a subsurface irrigation experiment, in which additional water was added to the drainage systems during the growing season to increase the water table level and mitigate greenhouse gas emissions.

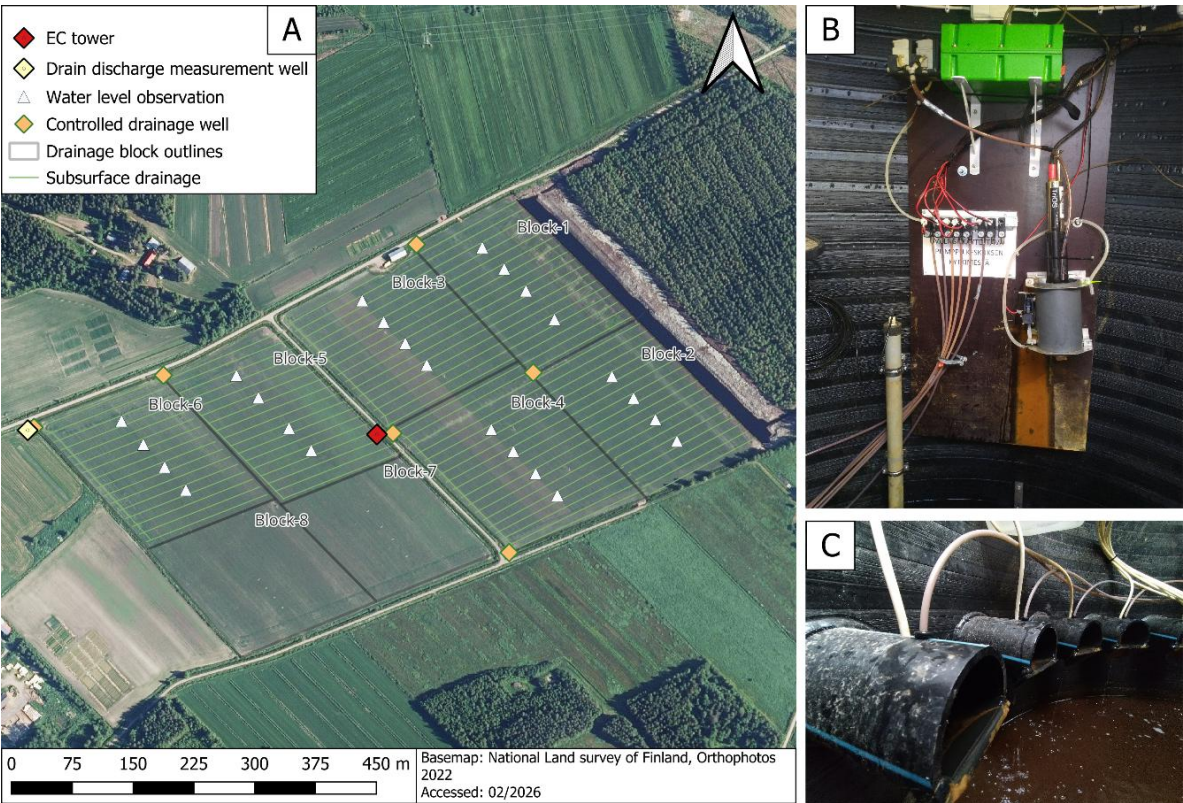




Figure 1. A) Overview of the NorPeat measurement field and locations of data sources. Along Blocks 1 and 2, the water reservoir used to supply additional water for irrigation during the growing season is visible. The drainage outlets from each drainage block were connected to the discharge measurement well with a subsurface pipe. B) Analyser, sampler, and sample holder located in the drainage measurement well. C) Drainage outlets to the drainage collection well. Tubing to the optical analyser is visible on top of the pipes.

In 2022, fields were sown with barley (*Hordeum vulgare*, var. “Vertti”) and fertilised 300 kg ha⁻¹ (20-2-12 N-P-K) granular mineral fertiliser on 9-10 June and harvested in September. On 21 September the field was sprayed with glyphosate and between 9-11 October field was ploughed, leaving fields without plant cover for winter.

In 2023, harrowing of the fields started on 15 May but was aborted due to wet conditions and finished on 22 May. On 29 May the field was sown with barley (var. “Hermanni”) and grass seed mixture consisting of 75 % *Phleum pratense* Var. “Tryggve” and 25 % *Festuca pratensis* Var. “Minto” and fertilised with 200 kg ha⁻¹ 20-2-12 N-P-K fertiliser. Between 30 August and 8 September fields were harvested, and grass was left in the field for winter. During 2024, fields were fertilised on 21 May with 400 kg ha⁻¹ 20-2-12 N-P-K fertiliser and on 17 July with 364 kg ha⁻¹ 22-0-12 N-P-K fertiliser. The field was harvested three times: first harvest on 14 July, second harvest on 2 August, and third harvest on 10 September.

The field is drained using subsurface drainage systems with adjustable weirs. In 2023, the drain outlets were set to an average depth of 80 cm for the entire field. Drain outlets were extended on 17 May 2024 to set the field average drainage depth to 30 cm.

2.2 Environmental monitoring

The drainage systems in the field were renewed in 2017, and the field was divided into six separate drainage blocks with discharge monitoring every 15 min. In August 2023, drainage collection expanded to include the remaining drainage blocks. Water levels were monitored hourly up to 2-meter depth with relative pressure sensors (Keller PR-26D) from four points in each drainage block. The monitoring points were at the midpoints of the subsurface drainage laterals. N₂O concentrations were measured by the Finnish Meteorological Institute (FMI) using an eddy covariance (EC) system located in the middle of the field. The details of the measurement system and data processing are described in Gerin et al. (2023). Continuous soil temperature measurements at -5 cm and -30 cm depths from the EC measurement location were retrieved from the Field Observatory (Nevalainen et al., 2022). Meteorological observations, such as precipitation, snow depth, and air temperature, were obtained from the FMI weather station (National ID 101787), located 400 m from the drainage collection point. The wind speed was observed at the side of the monitoring field.

2.3 Water quality monitoring

Drainage water from the drainage blocks is directed to the drainage collection well which houses the discharge measurements, flow-weighted sample pumps, and collectors. A commercial UV-absorbance sensor (Opus TriOS) using a 2 mm path length and custom multiplexing sampler was built to allow sampling and measurement of each individual drainage



125 block. An optical analyser and sampler system were installed in the drainage collection well in the spring of 2024 (Fig. 1 B and C). The sensor measures UV-absorbance spectra between 200 nm and 360 nm with 0.8 nm resolution. The sensor uses a proprietary method to utilise the entire spectrum to determine nitrate-N ($\text{NO}_3\text{-N}$) and dissolved organic carbon (DOC) concentrations. The measurement cycle was set to start every 30 min and each block was sampled and analysed in sequence. A mechanical wiper was programmed to clean the lenses of the sensor before each measurement. To minimise the mixing of
130 samples between each block, the tubes and valve manifold were first flushed with water from the currently measured block, then the analysis cup was purged, and finally the analyser cup was filled with the analysed sample. During the study period, the sensor lenses were cleaned once a week with basic and acidic solutions and a small brush to minimise the fouling of optical surfaces by organic compounds and rust precipitation.

During the measurement period, the measurements were stopped a few times. In August 2023, the collection well was
135 updated, forcing a maintenance break for the sampler and analyser. In October 2023, heavy rain flooded the collection well and monitoring system. In April 2024, rapid snowmelt flooded the fields again, causing a gap in drainage measurements. During the summer of 2024, the sampler occasionally provided sufficient samples for analysis. For measurements starting in October 2024, the lenses were thoroughly cleaned by submerging in oxalic acid solution for multiple days and wiping with lint-free paper. During cleaning, the sampler was restored to the working condition by completely dismantling and
140 thoroughly cleaning each component.

To assess the function of the sampler and analyser, a total of 50 water samples from running water at the drainage outlet between 30 May 2023 and 12 December 2024 were analysed for DOC and $\text{NO}_3\text{-N}$ concentrations at an accredited laboratory (Eurofins Ahma Oy). Analyses of DOC were performed according to the standard (SFS-EN ISO 1484, 1997) and for $\text{NO}_3\text{-N}$ (SFS-EN ISO 13395, 1996). Most calibration samples were from Block-4, with 12 samples, and the least number of samples
145 were from Block-6, with three individual samples (Supplementary Table S1).

2.4 Data processing

The measurement data were read from the data sampler controller system every few months. All data cleaning and analysis were performed using R version 4.5.2 (R Core Team, 2025) in the RStudio environment. The original 30-minute time series data, with parameters from the sensor, were averaged to an hourly time series and combined with the hourly average of
150 drainage discharge, water table depth, and soil temperature. Technical filtering of the N_2O raw data was performed by setting the required cell pressure to 70 – 110 Torr and filtering the values below the ambient threshold of 320 ppb. Raw data were aggregated to one minute resolution time series, and each minute was required to have at least 20 s of observations. These data were aggregated to hourly averages, and all hours with an average wind speed of less than 2.5 m s^{-1} were removed from the final dataset.

155 Optical sensor water quality data were manually quality controlled for sampler malfunctions and dry drain outlets. The periods when the measurements from all drainage blocks rapidly converged to the same value indicated sampler malfunction



and were removed from the data. During the dry periods, some drain outlets dried completely, making it impossible to extract samples for analysis. This is indicated by rapid fluctuations in the measurements and their removal from the data.



160 3 Results

3.1 Monitoring system and data quality

A two-year monitoring period with the optical sensor started on 11 April 2023 and ended on 15 April 2025. This period covers a total 17 645 possible hourly observations. After data processing Blocks 1-4 had usable observations ranging from 11 877 to 11 328. A smaller number of measurements were made from Block-5 (6 820 observations) and Block-6 (9 802 observations).

The overall fit of the linear model between the laboratory samples and in situ analyser $\text{NO}_3\text{-N}$ measurements was acceptable ($R^2 = 0.62$). In the block-wise assessment, $\text{NO}_3\text{-N}$ had satisfactory agreement with the laboratory analyses for drainage blocks 1-5 with R^2 ranging from 0.59 to 0.86. Samples from Block-6 showed poor agreement, but the number of samples was very small (Supplementary Fig. S1).

170 The relationship between the sensor and laboratory analysis for DOC was more complicated because the overall fit between the laboratory samples and sensor output with the linear model was poor ($R^2 = 0.17$). Splitting the calibration data for years 2023 and 2024 and omitting two groups of outliers from year 2023 improved the fit between laboratory analyses and sensor data, with $R^2 = 0.58$ and $R^2 = 0.72$ for years 2023 and 2024, respectively (Supplementary Fig. S2). Dissolved organic carbon was dropped from the analysis from this point onwards because of insufficient laboratory analyses to conduct a new calibration.

3.2 Seasonal NO_3 dynamics

Over the entire monitoring period, the average water table depth was 0.76 m and ranged from 0 m to 1.9 m, which is the maximum depth that the monitoring system can observe. Mean drain discharge was 0.52 mm d^{-1} , and it varied from 0 mm d^{-1} to 20.34 mm d^{-1} . Air temperature varied between 24°C and -33°C , but the minimum soil temperature at 5 cm depth was -1.7°C , which occurred during milder winter with smaller maximum snow cover. Typically, water table depth, drain discharge, and drainage $\text{NO}_3\text{-N}$ concentration varied together seasonally, with the highest values occurring in the spring during snowmelt and autumn before the development of snow cover.

Two of the four $\text{NO}_3\text{-N}$ leaching events were fully captured by the high-resolution drainage monitoring system. The first event occurred in April 2023, almost immediately after the measurements began. The drainage discharge started to increase rapidly after the snow started to melt, and a peak discharge of 11.8 mm d^{-1} and $\text{NO}_3\text{-N}$ concentration of 28.9 mg l^{-1} occurred while fields were still covered in snow. After the peak, the drainage $\text{NO}_3\text{-N}$ concentrations in the drainage started to decline steadily with the $\text{NO}_3\text{-N}$ concentrations from block drain water ranging within 10 mg l^{-1} from each other until mid-June when drainage $\text{NO}_3\text{-N}$ the plants started to grow, and the $\text{NO}_3\text{-N}$ concentration converged rapidly to 1.5 mg l^{-1} .

The next events were autumn and winter events in 2023 and 2024 which occurred before the development of snow cover. 190 The measurements during the Autumn 2023 leaching event were stopped when the largest observed daily precipitation of 42.6 mm flooded the drainage collection well. Peak drainage discharge and $\text{NO}_3\text{-N}$ concentrations were not recorded. The



tail of the autumn high $\text{NO}_3\text{-N}$ concentration extended to the snow-covered period, and there was still activity in the $\text{NO}_3\text{-N}$ concentration even with air temperature reaching -33°C . During the winter, $\text{NO}_3\text{-N}$ measurements from Block-2 were distinct from other blocks, with $\text{NO}_3\text{-N}$ fluctuating around 10 mg l^{-1} . In the other blocks, the drainage $\text{NO}_3\text{-N}$ concentration tended to stay between 1 and 5 mg l^{-1} . The average nitrate concentration in the drainage water during both winter periods was 2.2 mg l^{-1} and the highest concentrations were 17.5 mg l^{-1} and 19.5 mg l^{-1} during cold and mild winters, respectively. The last $\text{NO}_3\text{-N}$ leaching event occurred during winter between 2024 and 2025, when the drain outlet elevation was adjusted to average depth of 30 cm from the field surface to minimise the nutrient leaching through the drainage systems. Peak drain discharges (2.5 mm d^{-1}) were measured at the end of October, but the peak drainage $\text{NO}_3\text{-N}$ concentrations (20 mg l^{-1}) occurred a month later at the end of November and early December (Fig. 2, a and d).

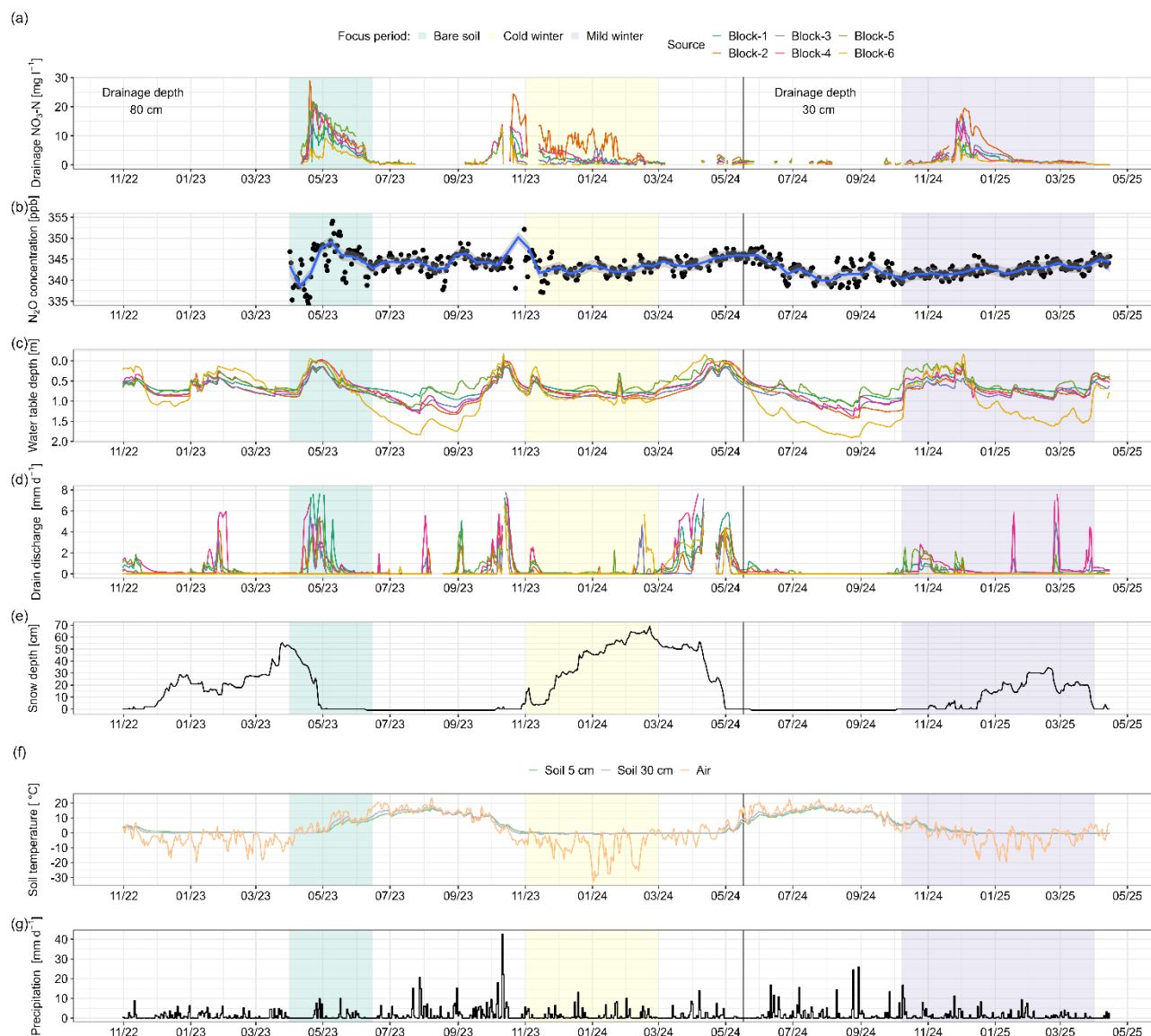


Figure 2. Monitoring data from the analysis period of 11/2022 – 04/2025. Highlighted periods with the best NO_3 concentration measurements, which are analysed in more detail. The vertical line shows the time when the drain depth was adjusted from an average depth of 80 cm to an average depth of 30 cm across the entire field. A) Drainage $\text{NO}_3\text{-N}$ concentrations [mg l^{-1}] from all blocks 1. B) Atmospheric N_2O concentrations [ppb] C) Daily water table depth. [m] D) Daily drain discharge [mm d^{-1}] 1. E) Snow depth at meteorological station [cm] F) Daily air and soil temperatures at depths of 5 cm and 30 cm. [$^{\circ}\text{C}$] G) Daily precipitation [mm d^{-1}]



210 **Table 1. Overall and seasonal means of weather, field conditions, and nitrogen related measurements. Values in parentheses indicate the full range of observations.**

		Overall N = 4,364 ^l	Bare Soil N = 383 ^l	Cold winter N = 732 ^l	Plant cover N = 2,196 ^l	Mild winter N = 1,053 ^l
Weather	Precipitation [mm d ⁻¹]	1.48 (0.00, 42.57)	1.04 (0.00, 10.11)	1.21 (0.00, 13.15)	1.81 (0.00, 42.57)	1.14 (0.00, 16.61)
	Air temperature [°C]	4 (-33, 24)	8 (0, 17)	-9 (-33, 3)	10 (-10, 24)	-2 (-20, 11)
	Snow depth [cm]	21 (0, 69)	8 (0, 41)	40 (3, 69)	20 (0, 56)	12 (0, 35)
Field condition	Drain discharge [mm d ⁻¹]	0.52 (0.00, 20.34)	0.97 (0.00, 11.84)	0.21 (0.00, 20.34)	0.66 (0.00, 10.48)	0.29 (0.00, 8.35)
	Water table depth [m]	0.76 (0.00, 1.90)	0.48 (0.00, 1.21)	0.78 (0.15, 1.09)	0.83 (0.00, 1.90)	0.70 (0.04, 1.62)
	Soil temperature 5 cm depth [°C]	5.5 (-1.7, 18.5)	5.6 (-0.1, 11.2)	-0.4 (-1.2, 0.0)	9.7 (-0.3, 18.5)	0.9 (-1.7, 8.8)
Nitrogen	N ₂ O concentration [ppb]	343.4 (334.2, 389.6)	345 (334.2, 354.1)	342.8 (337.1, 347.2)	343.8 (337.8, 389.6)	342.4 (339.2, 346.6)
	Drain NO ₃ -N concentration [mg l ⁻¹]	2.3 (0.0, 28.9)	7.9 (0.2, 28.9)	2.2 (0.0, 17.5)	1.4 (0.0, 24.5)	2.2 (0.0, 19.5)
	^l Mean (Min, Max)					



3.3 Drainage management impact to NO₃-N leaching

During the establishment of the new grass sward, the average drainage depth was 80 cm from the field surface, which was the minimum drainage depth of the factory made control well allowed. After the development of the new grass sward, the drainage depth was decreased to an average of 30 cm by extending the overflow weirs in the well. The maximum NO₃-N concentrations were 19.5 mg l⁻¹ during the period with 30 cm drainage depth and 28.9 mg l⁻¹. The drain discharge rate was reduced from 0.78 mm d⁻¹ during the 80 cm drainage depth period to 0.18 mm d⁻¹ during the 30 cm drainage outlet depth. There was no clear change in the water table depth due to the decreased drainage depth (Supplementary Table S2). The drain discharge was related to the water table depth, and this relationship was modified by adjusting the drainage depth. Discharge through subsurface drains was initiated in both cases when the water table depth decreases to 0.75 meters. When the drain outlets were set to 80 cm depth, drainage started to increase rapidly and reached up to 2.5 mm d⁻¹ when WTD reached the soil surface. During the reduced drainage depth, the drain discharge when the WTD was at the surface was near 1 mm d⁻¹ (Fig. 3 a.)

The drainage NO₃-N concentration tended to increase when the water table reached the soil surface with a clear cutoff at 1 m depth. Drainage NO₃-N concentrations above 5 mg l⁻¹ were only observed when WTD was less than 1 m from the field surface. The fitted curve for the 30 cm drainage depth was consistently below the curve fit for the 80 cm drainage depth period, indicating a persistent decrease in NO₃-N leaching during the later period. (Fig. 3 b.)

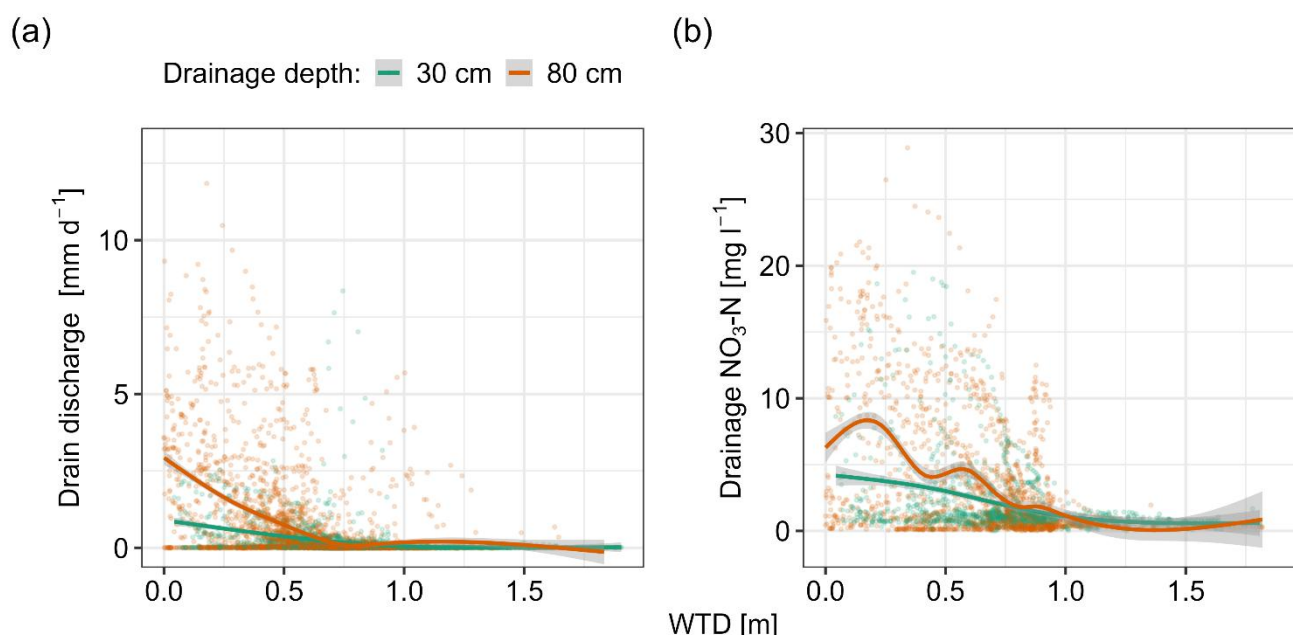


Figure 3. Relationship between water table depth and components of NO₃-N leaching during periods with different drainage depths. Lines show the GAM smoothing fitted to each drainage depth period separately. A) Subsurface drain discharge as a function of water table depth B) NO₃-N concentration in drainage water as a function of water table depth



3.4 Event and Spatial heterogeneity of leaching across blocks

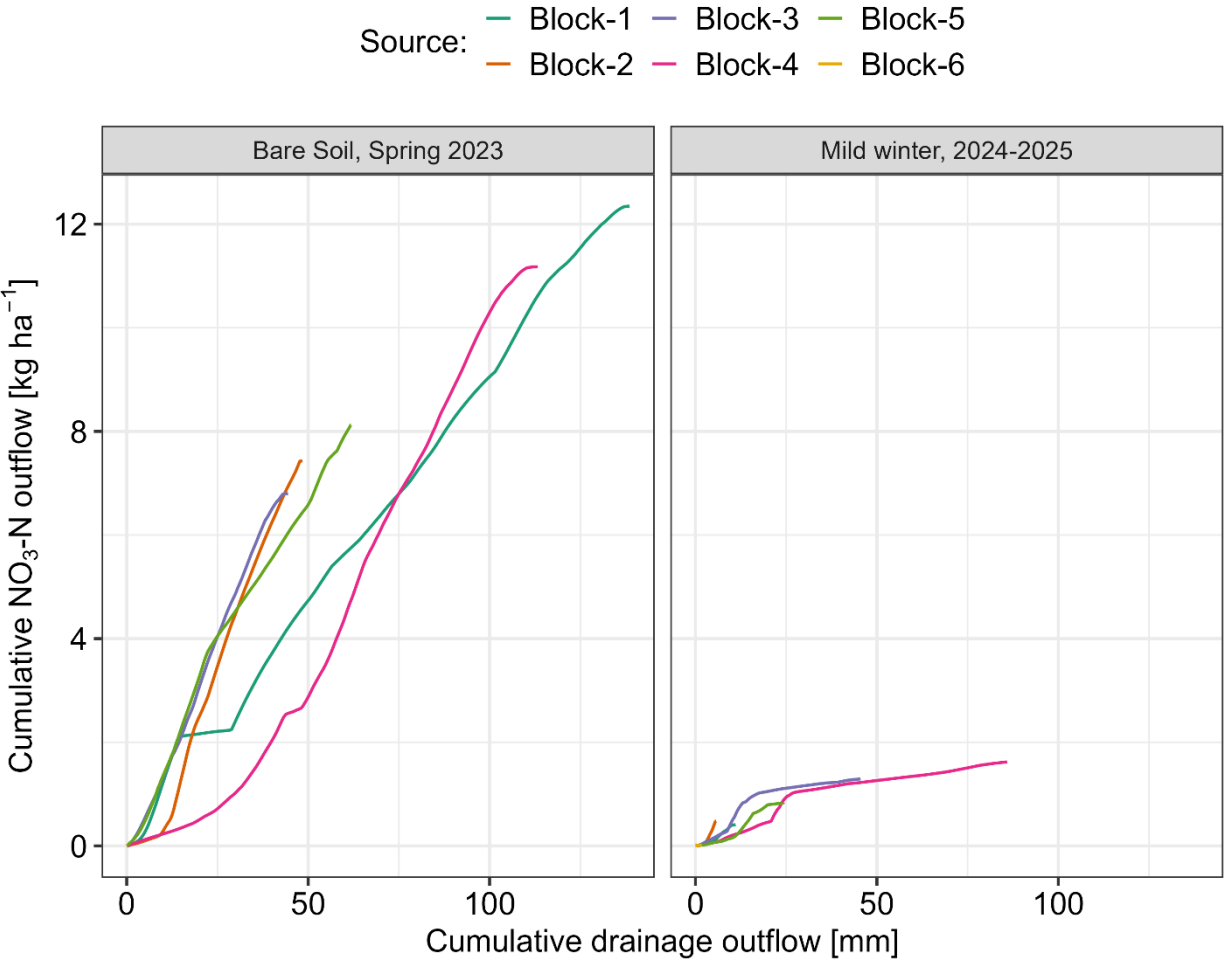
Over the whole monitoring period, the average drain discharge from shallow peat blocks (Blocks 3,5 and 6) was 0.05 mm d⁻¹ higher than that in the deep peat blocks (Blocks 1, 2, and 4), but the average nitrate concentration was 0.7 mg l⁻¹ higher in the deep peat blocks. The two-year average water table depth was almost the same for the deep and shallow peat blocks, but the maximum observed water table depth was 57 cm deeper in the shallow peat blocks. Over the two-year period average annual NO₃-N export was 4.75 kg NO₃-N ha⁻¹ year⁻¹ from deep peat blocks and 3.81 kg NO₃-N ha⁻¹ year⁻¹ shallow peat blocks.

Table 3. Measurements related to NO₃-N leaching over a two-year monitoring period divided by peat depth. Average water table depth, drain discharge, and NO₃-N concentration for two portions of the field with different peat depths. Deep peat included drainage blocks 1, 2, and 4, and shallow peat included measurements from drainage blocks 3, 5, and 6. To assess the nitrate output from the field gaps in the drain discharge, the NO₃-N concentration was linearly interpolated.

	Deep peat N = 2,205 ^l	Shallow peat N = 2,159 ^l
Drain discharge [mm d ⁻¹]	0.50 (0.00, 11.84)	0.55 (0.00, 20.34)
Water table depth [m]	0.75 (0.02, 1.43)	0.77 (0.00, 1.90)
NO ₃ -N [mg l ⁻¹]	2.6 (0.0, 28.9)	1.9 (0.0, 20.9)

Two of the three leaching events had nearly complete records of drain discharge and NO₃-N-concentrations from all drainage blocks. After interpolating over the missing gaps, a cumulative sum for the NO₃-N and drainage outputs was calculated for the spring 2023 melt event between 30 June 2023 and 11 April 2023 and winter between 24 April 2025 and 4 November 2024 for each drainage block. At the beginning of the spring of 2023, the field was covered with snow. Melting snow and precipitation during the event caused an average water input of 118 mm, ranging from 106 to 142 mm within the field. Cumulative sums were calculated for an 80-day period. Average water input intensity 1.5 mm d⁻¹. The average drainage outflow from the field was 68.7 mm ranging from 0.3 mm from Block-6 to 139 mm from Block-1. During the spring melt event NO₃-N leaching was on average 7.7 kg NO₃-N ha⁻¹ and ranged from 0.005 kg ha⁻¹ from Block-6 to 12.3 kg ha⁻¹ from Block-1 (Supplement Table S2). The melt event started with low NO₃-N concentration water in Blocks 2 and 4. Blocks 4 and 1 show a rapid increase in the drainage outflow. Overall, the NO₃-N output from the drainage blocks increased linearly with drain discharge generation. Water and NO₃-N output from Blocks 2,3 and 5 followed similar trajectories and ended at around 50 mm drain outflow and 7.5 kg NO₃-N ha⁻¹ (Fig. 4)

During the winter runoff activation period, the total water input was 142 mm. Cumulative sums were calculated over a 171-day period. The average water input intensity was 0.83 mm d^{-1} . Average drainage output from the blocks was 29.4 mm and ranging from 1.8 mm from the Block-6 to 86.8 mm from Block-4. During the winter period average $\text{NO}_3\text{-N}$ output was $0.78 \text{ kg NO}_3\text{-N ha}^{-1}$ ranging from $0.02 \text{ kg NO}_3\text{-N ha}^{-1}$ from Block-6 to $1.63 \text{ kg NO}_3\text{-N ha}^{-1}$ from Block-4 (Supplement Table S2). Outputs of $\text{NO}_3\text{-N}$ and runoff were the largest from Blocks 4,3 and 2. The dual-mass lines from these plots show a period of rapid increase in the $\text{NO}_3\text{-N}$ output. Blocks 3,4 and 5 with the highest drain outflows show an (Fig. 4.)



265 **Figure 4. Dual-mass curves for $\text{NO}_3\text{-N}$ and drainage outflow for each block. A) Spring snowmelt 2023 from field with bare soil B) $\text{NO}_3\text{-N}$ and water output during mild winter between 2024-2025 with average 30 cm drainage depth and plant cover in the field.**



3.5 Co-variation of drainage $\text{NO}_3\text{-N}$ and atmospheric N_2O concentrations

270 To assess the potential linkage between drainage $\text{NO}_3\text{-N}$ and air N_2O concentrations, the hourly average of all measurement blocks was calculated and compared with the hourly air N_2O concentration. Most of the observations were from times when average $\text{NO}_3\text{-N}$ concentrations were less than 5 mg/l and air N_2O concentrations were between 340-345 ppb. Elevated N_2O concentrations rarely occurred in air (Supplementary Fig. S3).

275 Elevated N_2O concentrations were observed together with high drainage nitrate concentrations only during the period with bare soil in the beginning of the monitoring period from 1 April 2023 to 15 June 2023. A peak N_2O concentration of 360 ppb occurred when the soil temperature was above 5 °C and drainage nitrate concentration was approximately 10 mg l⁻¹. The maximum field average $\text{NO}_3\text{-N}$ concentration reached 20 mg l⁻¹, but the air N_2O concentrations started to decline from the peak concentrations together with soil temperature. Similar conditions with increased $\text{NO}_3\text{-N}$ concentrations and elevated soil temperatures were observed during the plant-covered period, but without an indication of increased N_2O concentrations. During the mild winter, the range of drainage $\text{NO}_3\text{-N}$ concentrations was between 0 and 12 mg l⁻¹. During the cold winter 280 drainage $\text{NO}_3\text{-N}$ concentrations ranged between 0-6 mg l⁻¹. No instantaneous co-variation with air N_2O and drainage $\text{NO}_3\text{-N}$ was observed during either winter period (Fig. 5).

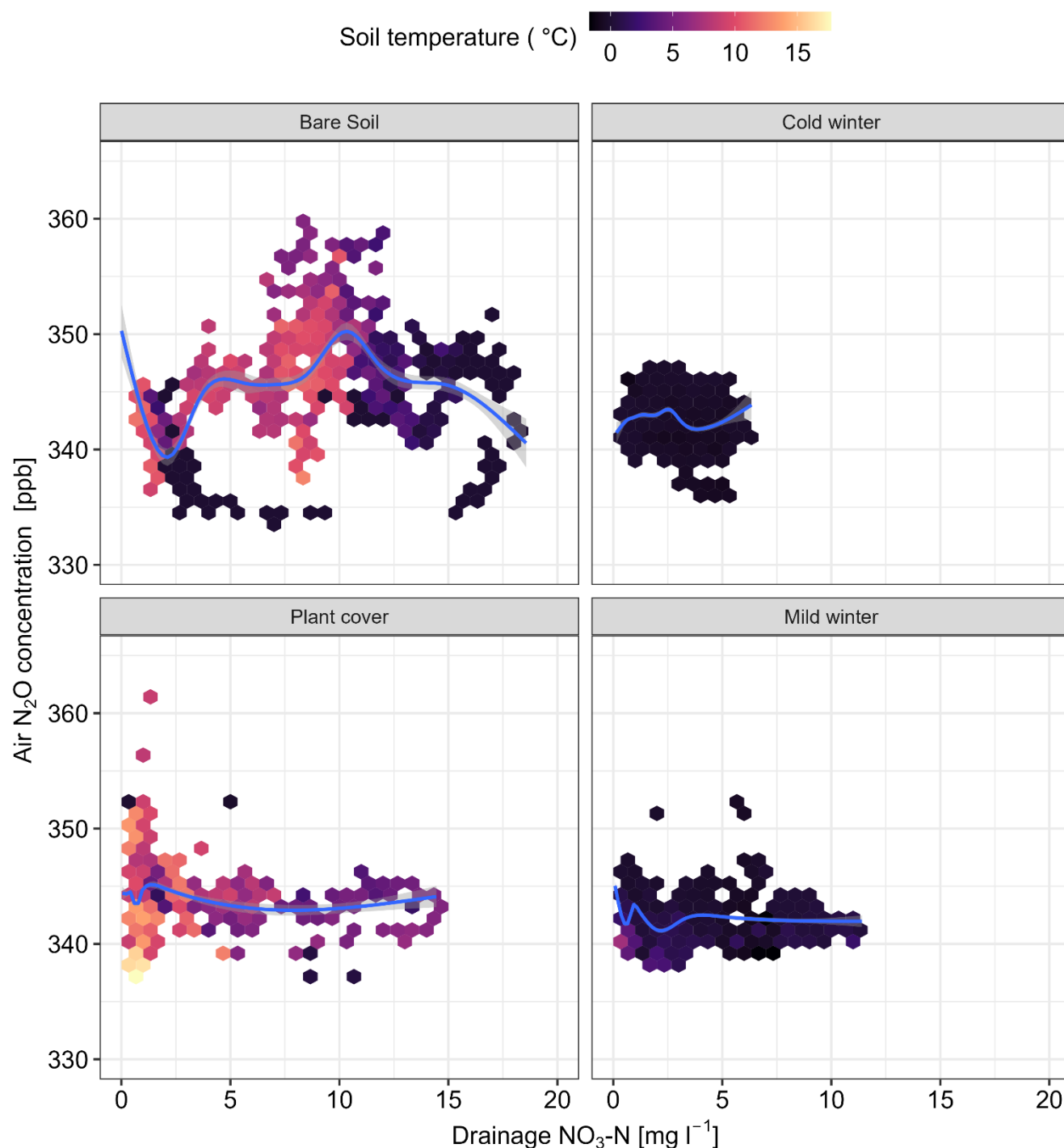


Figure 5. Heatmap of N_2O and $\text{NO}_3\text{-N}$ measurements during different winter and plant coverage periods in the field. The mean atmospheric N_2O concentration during the monitoring period was 343.4 ppb. The colour of the bin indicates the average soil temperature at 5 cm depth for observations that are placed in the bin.



4 Discussion

Drained peat soils are major contributors to national GHG emissions and eutrophication in local waterbodies (van Giersbergen et al., 2025; Silverthorn et al., 2026), and better management practices and process understanding are needed to control minimize impact. This study shows that ecosystem scale nitrogen losses from cultivated peatland were highly episodic and that the controls on nitrate export and atmospheric N₂O were only partly shared. These findings are discussed below in relation to (i) hydrological controls on runoff and nitrate export and the effect of drainage depth management, (ii) the seasonal coupling between drainage NO₃⁻N and atmospheric N₂O, and (iii) implications for monitoring design in the context of boreal cultivated peatlands.

4.1 Drainage depth management reshapes water-table controls on runoff and nitrate

The relationship between the water table depth to drain runoff and NO₃-N concentration showed a distinct threshold depth for flow initiation, followed by increasing runoff as the water table reached the soil surface. Drain runoff sensitivity to water table depth represents a bottom-up control for runoff generation, which means that groundwater contributes to the generation of drain runoff (Cain et al., 2022). Increasing the average drainage depth by 50 cm to minimise water losses through the drainage system and increase water levels in the field was not reflected in the observed threshold depth, but the drainage runoff increased at a slower rate after the cutoff was reached.

Consequently, drain runoff and nitrate leaching were concentrated to the wet seasons in autumn and spring after snowmelt. In this case, a large majority of the NO₃-N losses through drainage systems occurred during the first spring over an 80-day long period with an average NO₃-N output of 7.7 kg NO₃-N ha⁻¹. Previously, it has been demonstrated that the top 10 % of the highest drain discharge rates can transport more than 50 % of the total NO₃-N during the monitoring period (Liu et al., 2020). During the growing season, drain discharge and nitrate concentrations were typically low due to high nitrogen uptake of the growing grassland and high soil moisture deficit in the soil water storages due to high ET. For the period after the drainage depth adjustment was mostly reflected on the drain runoff generation and less on the drainage NO₃-N concentration, which is commonly found in controlled drainage research studies (Carstensen et al., 2020).

Peat depth has been linked to the total amount of nitrogen and NO₃-N leaching at this site (Pham et al., 2023; Yli-Halla et al., 2022). High resolution water quality sensor data support these observations and provide additional process understanding for the generation of the nitrate leaching. Shallow WTD is shared with elevated NO₃-N concentrations and runoff generation. Largest difference caused by the peat depth was in the NO₃-N concentration. Most of the nitrogen stock is stored in the peat layer so it is likely that with deeper peat horizon elevated drainage NO₃-N concentration starts earlier and last longer as the field gets saturated.

However, the coupling between the nitrate output and drain runoff is not absolute as during the last leaching event, in the autumn of 2024 the peak drainage discharge occurred one month before peak NO₃-N concentrations. During the event, grassland was fully developed and soil temperature was above 5 °C, facilitating grassland N uptake. Before the nitrate



concentration peak, soil temperature had declined to close to 0 °C, and the field was briefly covered in snow. Between the drainage discharge rate peak and concentration peak conditions were sufficient for nitrate accumulation and eventual release as the water table reached the surface.

4.2 Controls on the co-variation of drainage NO_3^- -N and atmospheric N_2O

Simultaneous high-frequency observations of drainage NO_3^- -N and atmospheric N_2O concentrations revealed a hotspot moment for nitrogen loss, where both loss pathways were simultaneously active. Co-variation was observed during the first monitoring spring, during conditions after snowmelt with bare tilled soil, and soil temperature well above freezing. During snowmelt, the peak in drainage NO_3^- -N preceded the peak in atmospheric N_2O , indicating the presence of NO_3^- -N in the soil before soil conditions became fully favourable for active denitrification.

This temporal offset suggests that hydrological flushing and gaseous nitrogen production were linked through substrate availability but operated on different timescales. The flushing of nitrate is controlled by the activation of hydrological flow paths. Exceptionally high NO_3^- -N output during the hotspot spring suggests the accumulation of nitrate during winter and preceding autumn. To activate the denitrification of available NO_3^- -N to N_2O , an additional constraint of soil temperature was required, as the highest N_2O concentrations were observed at a soil temperature of approximately 5 °C. Temperature, nitrate concentration, and soil moisture are well-established factors that control production of N_2O (Butterbach-Bahl et al., 2013)

Periodic renewal is the most drastic management action during the lifecycle of managed grasslands and has been under scrutiny from both N_2O emissions and nitrate leaching perspectives (Buchen et al., 2017). The main observation of high N_2O emissions after renewal has been previously observed by Offermanns et al. (2023), who reported exceptionally high annual N_2O fluxes during grassland renewal. Renewal of grassland over the winter instead of summer has been shown to be a worse option for N_2O emissions (Semberg et al., 2026), suggesting that the winter period is a meaningful time for the accumulation of nitrate. This is feasible as snowpack provides an insulating layer to the soil and in this case the lowest soil temperature at 5 cm depth was -1.7 °C, in which mineralisation and nitrification can still occur at relevant rates (Clark et al., 2009).

However, the relationship was not persistent across seasons, even with similar nitrate concentrations in the drainage system. The lack of clear co-variation during winter also highlights the importance of thermal limitations. Although drainage NO_3^- -N remained detectable during both mild and cold winter periods, atmospheric N_2O concentrations showed no corresponding increase. This is consistent with the view that denitrification in boreal cultivated peat soils is constrained during winter by low soil temperatures, even when nitrate and moisture are present (Gerin et al., 2023).

N_2O concentrations were used as a proxy for activity related to N_2O production. This has limited our capabilities to detect the smallest fluxes, but we believe this is the best available data to highlight the hotspot moments for emissions that arise from hydrology, weather conditions, agricultural management, and plant processes. Accurate measurement of N_2O fluxes is notoriously difficult, with inherent trade-offs between spatial or temporal resolution and minimum detectable fluxes (Butterbach-Bahl et al., 2013). For example, eddy covariance methods can provide observations from large areas, consistent with the water quality observation data used here, but quality-controlled flux datasets tend to have approximately half or less



of all potential observations (Cowan et al., 2025; Gerin et al., 2023). Future work should aim to connect the gaseous fluxes with the drainage fluxes, as the potential gains for model development and practical applications are apparent.

Overall, our results indicate that the co-variation between drainage $\text{NO}_3\text{-N}$ and atmospheric N_2O emerged only under a restricted set of conditions: hydrological connectivity sufficient to mobilise nitrate, soil temperatures high enough to support microbial activity, and limited plant nitrogen uptake. Our observations suggest that nitrate export responds most directly to hydrological connectivity and snowmelt-driven flushing, whereas N_2O production is constrained by plant uptake, temperature, and soil moisture conditions, which regulate microbial activity and complete denitrification. Outside these conditions, aquatic and atmospheric nitrogen loss pathways became decoupled. This has important implications for both mitigation and modelling, as it suggests that periods of high nitrate leaching do not necessarily correspond to periods of high N_2O emissions, and vice versa. For agricultural management it seems that maintaining growing vegetation is necessary to reduce nitrogen based losses. With grassland management this means longer renewal interval and planting cover crops with perennial crops can have mitigation impact

4.4 Monitoring limitations and implications for future observations and modelling

The optical monitoring system used in this study was successful in acquiring high-frequency nitrate data from multiple drainage blocks and revealed event-scale dynamics that would likely have remained unresolved with conventional sampling. This is a key strength of the approach, as nitrogen export from cultivated peatlands has been shown to be concentrated in short periods of hydrological activation. At the same time, the study also highlighted important operational and interpretative limitations that should be considered when designing future monitoring systems for drained organic soils.

Optical sensors are indirect measurements of the parameter of interest. The quality of the high-resolution dataset is always dependent on the quality of the calibration dataset and maintenance procedures. Reliable detection of dissolved carbon was shown to be difficult in this context as contributed by the known site-specific and time-varying structure of dissolved carbon (Vaughan et al., 2017), interference from dissolved iron (Poulin et al., 2014), and the establishment of permanent fouling on the optical surfaces which required annual wash cycles and lens replacement over the research period.

Organic soil layer on top of acid sulfate-affected clay results in high concentrations of dissolved organic compounds and high concentration of dissolved iron, and intermittent runoff from the drains are the most important site characteristics that affect the performance of the sensor optical surfaces and lifespan of the sampling valve manifold. Future monitoring systems in drained peatlands should consider the intermittent nature of the activation of drainage flow as a starting point and use flow-activated sampling strategies. In addition, automated cleaning, such as periodic acid flushing combined with mechanical wiping, is likely necessary to reduce permanent fouling on optical surfaces (Liu et al., 2020). Our monitoring system can only report nitrate fluxes from the drain outlets. Other flow paths, such as seepage to surrounding ditches and deeper groundwater or increased surface runoff, may also be increased by decreased drainage depth (Rozemeijer et al., 2016). Despite these limitations, the presented dataset has clear value for process understanding and model development. High-frequency concentration measurements provide information on event timing, hysteresis, and threshold behaviour that is often



missed in low-frequency observations, yet is essential for testing and improving process-based models of nitrogen mobilisation and transport (Husic et al., 2023) or N₂O emissions that remain difficult to model even with flux data (Kajasilta et al., 2026). In cultivated peatlands, where hydrological connectivity, management, and biological uptake interact strongly, such datasets are particularly important for identifying when nitrogen loss pathways are coupled and decoupled. Future monitoring networks should therefore prioritise both temporal resolution and measurement robustness while explicitly considering the peat-specific chemical and hydrological conditions that challenge sensor performance.

5 Conclusions

To our knowledge, this is the first study to connect nitrogen-based emissions through subsurface drainage systems to the atmosphere from cultivated peatlands at the field ecosystem scale. The monitoring data showed the central role of grassland nitrogen uptake in modulating nitrogen-based environmental loading, as the activities related to grassland renewal resulted in simultaneous gaseous and aqueous losses. Decreasing the drainage depth and maintaining well-growing vegetation are simple actions for farmers to reduce nitrogen-based leaching from cultivated organic soils.

The functioning of optical water quality sensors in this context and the unique dataset provided new insights into ecosystem-level co-variation of atmospheric and hydrological flow paths of nitrogen-based emissions from cultivated peatlands. This study can be used as a template for improved monitoring of agricultural systems, as it demonstrates the peat-specific complexities that need to be addressed in future studies.

High nitrate export was concentrated in runoff events outside the growing season, especially during snowmelt under bare soil conditions, whereas elevated N₂O concentrations occurred only when nitrate availability coincided with suitable thermal conditions. In addition, raising the drainage outlet reduced discharge more than nitrate concentrations, indicating that hydrological transport and biogeochemical nitrate supply responded differently to drainage management



405 **Code and data availability**

Research data and scripts for recreating the tables and figures can be accessed from (Läpikivi et al., 2026)

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

410 MLä: Writing (original draft preparation)

MN: Writing (original draft preparation), Writing (review and editing)

MLi: Conceptualization, Writing (review and editing)

VH: Resources, Writing (review and editing)

HA Data curation (N₂O data), Writing (review and editing)

415 HM: Conceptualization, Supervision, Writing (review and editing), funding, resources

BK: Conceptualization, Supervision, Writing (review and editing)

Competing interests

The authors declare that they have no conflict of interest.

Disclaimer

420 Copernicus Publications adds a standard disclaimer: “Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.”

Please feel free to add disclaimer text at your choice, if applicable.

425 **Acknowledgements**

We acknowledge the work of Erkki Joki-Tokola and Staff of Luke Ruukki research infrastructure for managing the NorPeat facility, University of Oulu workshop for manufacturing the analyser sample holder, Maria Honkakoski for aerial photography and Jusa Kokko for sensor and sampler maintenance.



Financial support

430 RATKU (grant no. A76859) project funded by the European Regional Development Fund (ERDF). ViljaPäästö (grant no.
19044) from European Agricultural Fund for Rural Development (EAFRD) through Centre for Economic Development,
Transport and the Environment, Finland. Visio (grant no. J11119) from Just Transition Fund through Council of Oulu
Region. We acknowledge the ACCC Flagship funding at the Research Council of Finland (grant nos. 357904 & 359342),
Business Finland (AGCLIMATE, grant no. 7017/31/2024) and Salaojituksen Tukisäätiö sr and Maa- ja vesitekniikan tuki for
435 supporting the work and platform development.

Review statement



References

- 440 AnaEE-ERIC, <https://www.anaee.eu/>, last access: 11 March 2026., 2026.
- Buchen, C., Well, R., Helfrich, M., Fuß, R., Kayser, M., Gensior, A., Benke, M., and Flessa, H.: Soil mineral N dynamics and N₂O emissions following grassland renewal, *Agriculture, Ecosystems & Environment*, 246, 325–342, <https://doi.org/10.1016/j.agee.2017.06.013>, 2017.
- Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, *Phil. Trans. R. Soc. B*, 368, 20130122, <https://doi.org/10.1098/rstb.2013.0122>, 2013.
- Cain, M. R., Woo, D. K., Kumar, P., Keefer, L., and Ward, A. S.: Antecedent Conditions Control Thresholds of Tile-Runoff Generation and Nitrogen Export in Intensively Managed Landscapes, *Water Resources Research*, 58, e2021WR030507, <https://doi.org/10.1029/2021WR030507>, 2022.
- 450 Carstensen, M. V., Hashemi, F., Hoffmann, C. C., Zak, D., Audet, J., and Kronvang, B.: Efficiency of mitigation measures targeting nutrient losses from agricultural drainage systems: A review, *Ambio*, 49, 1820–1837, <https://doi.org/10.1007/s13280-020-01345-5>, 2020.
- Clark, K., Chantigny, M. H., Angers, D. A., Rochette, P., and Parent, L.-É.: Nitrogen transformations in cold and frozen agricultural soils following organic amendments, *Soil Biology and Biochemistry*, 41, 348–356, <https://doi.org/10.1016/j.soilbio.2008.11.009>, 2009.
- 455 Cowan, N., Cumming, A., Morrison, R., Clilverd, H., Palmer, L., and Evans, C. D.: Measuring Fluxes of Nitrous Oxide (N₂O) From an Intensively Farmed Wasted Peatland Field in the UK Using the Eddy Covariance Method, *Global Change Biology*, 31, e70619, <https://doi.org/10.1111/gcb.70619>, 2025.
- Freeman, B. W. J., Evans, C. D., Musarika, S., Morrison, R., Newman, T. R., Page, S. E., Wiggs, G. F. S., Bell, N. G. A., Styles, D., Wen, Y., Chadwick, D. R., and Jones, D. L.: Responsible agriculture must adapt to the wetland character of mid-latitude peatlands, *Global Change Biology*, 28, 3795–3811, <https://doi.org/10.1111/gcb.16152>, 2022.
- 460 Frick, H., Oberson, A., Frossard, E., and Bünemann, E. K.: Leached nitrate under fertilised loamy soil originates mainly from mineralisation of soil organic N, *Agriculture, Ecosystems & Environment*, 338, 108093, <https://doi.org/10.1016/j.agee.2022.108093>, 2022.
- 465 Gerin, S., Vekuri, H., Liimatainen, M., Tuovinen, J.-P., Kekkonen, J., Kulmala, L., Laurila, T., Linkosalmi, M., Liski, J., Joki-Tokola, E., and Lohila, A.: Two contrasting years of continuous N₂O and CO₂ fluxes on a shallow-peated drained agricultural boreal peatland, *Agricultural and Forest Meteorology*, 341, 109630, <https://doi.org/10.1016/j.agrformet.2023.109630>, 2023.
- van Giersbergen, Q., Barthelmes, A., Couwenberg, J., Lång, K., Martin, N., Tegetmeyer, C., Fritz, C., and Tanneberger, F.: 470 Identifying hotspots of greenhouse gas emissions from drained peatlands in the European Union, *Nature Communications*, 16, 10825, <https://doi.org/10.1038/s41467-025-65841-6>, 2025.



- Holzknicht, A., Land, M., Dessureault-Rompré, J., Elsgaard, L., Lång, K., and Berglund, Ö.: Effects of converting cropland to grassland on greenhouse gas emissions from peat and organic-rich soils in temperate and boreal climates: a systematic review, *Environ Evid*, 14, 1, <https://doi.org/10.1186/s13750-024-00354-1>, 2025
- 475 Honkanen, H., Kekkonen, H., Heikkinen, J., Kaseva, J., and Lång, K.: Minor effects of no-till treatment on GHG emissions of boreal cultivated peat soil, *Biogeochemistry*, 167, 499–522, <https://doi.org/10.1007/s10533-023-01097-w>, 2024.
- Husic, A., Fox, J. F., Clare, E., Mahoney, T., and Zarnaghsh, A.: Nitrate Hysteresis as a Tool for Revealing Storm-Event Dynamics and Improving Water Quality Model Performance, *Water Resources Research*, 59, e2022WR033180, <https://doi.org/10.1029/2022WR033180>, 2023.
- 480 Jokinen, P., Pirinen, P., Kaukoranta, J.-P., Kangas, A., Alenius, P., Eriksson, P., Johansson, M., and Wilkman, S.: Climatological and oceanographic statistics of Finland 1991–2020, Finnish Meteorological Institute, <https://doi.org/10.35614/isbn.9789523361485>, 2021.
- Kajasilta, H., Gerin, S., Niiranen, M., Läpikivi, M., Liimatainen, M., Kraus, D., Vekuri, H., Korkiakoski, M., Kulmala, L., Liski, J., and Vira, J.: The effects of peat thickness and water table depth on CO₂ and N₂O emissions from agricultural
- 485 peatlands – a process-based modelling approach, *Biogeosciences*, 23, 3567–3590, <https://doi.org/10.5194/bg-23-3567-2026>, 2026
- Keck, H., Meurer, K. H. E., Jordan, S., Kätterer, T., Hadden, D., and Grelle, A.: Setting-aside cropland did not reduce greenhouse gas emissions from a drained peat soil in Sweden, *Frontiers in Environmental Science*, 12, <https://doi.org/10.3389/fenvs.2024.1386134>, 2024.
- 490 Leifeld, J. and Menichetti, L.: The underappreciated potential of peatlands in global climate change mitigation strategies, *Nature Communications*, 9, 1071, <https://doi.org/10.1038/s41467-018-03406-6>, 2018.
- Liu, W., Youssef, M. A., Birgand, F. P., Chescheir, G. M., Tian, S., and Maxwell, B. M.: Processes and mechanisms controlling nitrate dynamics in an artificially drained field: Insights from high-frequency water quality measurements, *Agricultural Water Management*, 232, 106032, <https://doi.org/10.1016/j.agwat.2020.106032>, 2020.
- 495 Läpikivi, M., Liimatainen, M., Niiranen, M., Hyöky, V., Aaltonen, H., Klöve, B., and Marttila, H.: High resolution nitrate concentration measurements from a drained cultivated peatland, <https://doi.org/10.5281/zenodo.22764821>, 2026.
- Nevalainen, O., Niemitalo, O., Fer, I., Juntunen, A., Mattila, T., Koskela, O., Kukkamäki, J., Höckerstedt, L., Mäkelä, L., Jarva, P., Heimsch, L., Vekuri, H., Kulmala, L., Stam, Å., Kuusela, O., Gerin, S., Viskari, T., Vira, J., Hyväluoma, J., Tuovinen, J.-P., Lohila, A., Laurila, T., Heinonsalo, J., Aalto, T., Kunttu, I., and Liski, J.: Towards agricultural soil carbon
- 500 monitoring, reporting, and verification through the Field Observatory Network (FiON), *Geosci. Instrum. Method. Data Syst.*, 11, 93–109, <https://doi.org/10.5194/gi-11-93-2022>, 2022.
- Offermanns, L., Tiemeyer, B., Dettmann, U., Rüffer, J., Düvel, D., Vogel, I., and Brümmer, C.: High greenhouse gas emissions after grassland renewal on bog peat soil, *Agricultural and Forest Meteorology*, 331, 109309, <https://doi.org/10.1016/j.agrformet.2023.109309>, 2023.



- 505 Olesen, J. E. and Bindi, M.: Consequences of climate change for European agricultural productivity, land use and policy, *European Journal of Agronomy*, 16, 239–262, [https://doi.org/10.1016/S1161-0301\(02\)00004-7](https://doi.org/10.1016/S1161-0301(02)00004-7), 2002.
- Pham, T., Yli-Halla, M., Marttila, H., Lötjönen, T., Liimatainen, M., Kekkonen, J., Läpikivi, M., Klöve, B., and Joki-Tokola, E.: Leaching of nitrogen, phosphorus and other solutes from a controlled drainage cultivated peatland in Ruukki, Finland, *Science of the Total Environment*, 904, <https://doi.org/10.1016/j.scitotenv.2023.166769>, 2023.
- 510 Poulin, B. A., Ryan, J. N., and Aiken, G. R.: Effects of Iron on Optical Properties of Dissolved Organic Matter, *Environmental Science & Technology*, 48, 10098–10106, <https://doi.org/10.1021/es502670r>, 2014.
- R Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, <https://www.R-project.org/>, 2025.
- Rozemeijer, J. C., Visser, A., Borren, W., Winegram, M., van der Velde, Y., Klein, J., and Broers, H. P.: High-frequency
- 515 monitoring of water fluxes and nutrient loads to assess the effects of controlled drainage on water storage and nutrient transport, *Hydrol. Earth Syst. Sci.*, 20, 347–358, <https://doi.org/10.5194/hess-20-347-2016>, 2016.
- Semberg, S., Bhattarai, H. R., Manninen, P., Li, Y., Shurpali, N., and Virkajärvi, P.: Timing of grass renewal regulates nitrous oxide emissions from a drained boreal peatland, *Agriculture, Ecosystems & Environment*, 399, 110155, <https://doi.org/10.1016/j.agee.2025.110155>, 2026.
- 520 Silverthorn, T., Aberg, D., Baker, F., Bell, C., Evans, C. D., Gurd, C., Holman, I., Howell, G., McEwen, A., Morrison, R., Oakley, J., Southon, F., and Peacock, M.: Land-Use Effects on Surface Water Quality in Temperate Lowland Peatlands, *Global Change Biology*, 32, e70988, <https://doi.org/10.1111/gcb.70988>, 2026.
- Vaughan, M. C. H., Bowden, W. B., Shanley, J. B., Vermilyea, A., Sleeper, R., Gold, A. J., Pradhanang, S. M., Inamdar, S. P., Levia, D. F., Andres, A. S., Birgand, F., and Schroth, A. W.: High-frequency dissolved organic carbon and nitrate
- 525 measurements reveal differences in storm hysteresis and loading in relation to land cover and seasonality, *Water Resources Research*, 53, 5345–5363, <https://doi.org/10.1002/2017WR020491>, 2017.
- Velthof, G. L., Hoving, I. E., Dolfing, J., Smit, A., Kuikman, P. J., and Oenema, O.: Method and timing of grassland renovation affects herbage yield, nitrate leaching, and nitrous oxide emission in intensively managed grasslands, *Nutrient Cycling in Agroecosystems*, 86, 401–412, <https://doi.org/10.1007/s10705-009-9302-7>, 2010.
- 530 Virkajärvi, P., Rinne, M., Mononen, J., Niskanen, O., Järvenranta, K., and Sairanen, A.: Dairy production systems in Finland, in: *Grassland and forages in high output dairy farming systems*, 18th Symposium of the European Grassland Federation, Wageningen, Netherlands, 15–17 June 2015, 51–66, <https://www.europeangrassland.org/en/infos/printed-matter/proceedings.html>, 2015.
- Yli-Halla, M., Lötjönen, T., Kekkonen, J., Virtanen, S., Marttila, H., Liimatainen, M., Saari, M., Mikkola, J., Suomela, R.,
- 535 and Joki-Tokola, E.: Thickness of peat influences the leaching of substances and greenhouse gas emissions from a cultivated organic soil, *Science of The Total Environment*, 806, 150499, <https://doi.org/10.1016/j.scitotenv.2021.150499>, 2022.