



Rewetting effects on the spatial variability and partitioning of carbon fluxes in a drained boreal peatland

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ABSTRACT

Fennoscandia has a long history of draining peatlands to increase forest production. Since these areas are potentially large sources of carbon dioxide (CO₂), rewetting is considered as a strategy for mitigating these emissions. However, empirical data on how rewetting affects the spatial variability and partitioning of the carbon (C) cycle components, including production, respiration and methane (CH₄) fluxes, are largely missing, in particular for minerogenic boreal peatlands. In this study, we addressed this knowledge gap by conducting chamber measurements of C fluxes over one growing season prior (2020) and two following (2021–2022) the rewetting of a minerogenic drained peatland forest in boreal Sweden. Our results show that higher water table level (WTL) following rewetting led to increased daytime net CO₂ uptake, driven by increased gross primary production, as well as to enhanced CH₄ emissions. Furthermore, heterotrophic respiration decreased in the second year after rewetting, whereas total forest-floor respiration remained similar due to a concurrent increase in its autotrophic component. We further found that rewetting impacts on CO₂ and CH₄ fluxes were highest closest to the ditch, however, no consistent gradient with distance from the ditch was observed. Instead, spatial variations of C fluxes were more closely related to specific local environmental conditions. Thus, our study highlights a spatially non-uniform response of all C cycle components during the initial years following rewetting. This poses a challenge for process-based modelling and the application of default emission factors for evaluating rewetting effects on the peatland C cycle.

1. Introduction

Peatlands play an important role in the global carbon (C) cycle since they store about 25% of the global soil C on less than 3% of the Earth's land surface (Yu et al., 2010; Xu et al., 2018). Natural peatlands have a climate cooling impact since they are a sink for carbon dioxide (CO₂) that in the long-term outweighs the emissions of methane (CH₄) (Frolking and Roulet, 2007). Historically, however, peatlands were considered to be unproductive lands and therefore extensively drained to increase agricultural and forest production (Succow and Joosten, 2001). In Fennoscandia, around 6 million ha of peatlands, equivalent to 40% of all peatlands were drained for timber production (Minkinen et al., 2008; Hånell 2009), with a network of almost half a million km of ditches alone in Sweden (Laudon et al., 2022). Today, these drained peatlands act as large C sources, contributing 5% of the EU's anthropogenic greenhouse gas (GHG) emissions (Greifswald Mire Centre, 2020). To mitigate the climate impact of drained peatlands, rewetting is considered as a strategy to reduce these C emissions (Günther et al.,

2020; Laudon et al., 2025). The Swedish government has identified peatland rewetting as part of its strategy to reduce GHG emissions in the land use sector by committing to rewet 100 000 ha (Government of Sweden, 2020). At present, however, a detailed empirical understanding of rewetting effects on the peatland C cycle and GHG balance is lacking.

Previous studies show that rewetted peatlands commonly exhibit initially higher CH₄ emissions and lower CO₂ emissions relative to drained conditions (Urbanová et al. 2013; Koskinen et al., 2016; Laine et al., 2019; Jurasinski et al., 2020; Escobar et al., 2022). However, empirical evidence for the climate effects from rewetting minerogenic peatlands in the boreal region is to our knowledge limited to a few studies conducted primarily in Finland, where most drainage activities were conducted a few decades ago (Komulainen et al., 1998, 1999; Nyberg et al., 2022; Purre et al. 2019b), whereas more studies have explored rewetting effects on GHG fluxes in former peat extraction areas that were subject to vegetation removal (Järveoja et al., 2016; Nugent et al., 2018; Wilson et al., 2022). However, since minerogenic peatland forests in Sweden have been drained about 100 years ago with remnant

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vegetation present, results from rewetted peatlands in Finland and from restored peat extraction areas may not be directly transferrable to long-term drained peatland forests in Sweden.

Furthermore, while previous rewetting studies examined the main CO₂ cycle components, including gross primary production (GPP) and ecosystem respiration (Reco) (Komulainen et al., 1998, 1999), the effects of rewetting on the individual respiration components, namely heterotrophic (Rh) and autotrophic (Ra) respiration, remain poorly understood. Knowledge of their separate responses to rewetting is, however, especially important in drained vegetated peatlands, to disentangle effects on peat decomposition from those related to vegetation changes (Hermans et al., 2022; Järveoja et al., 2016).

Peatland CO₂ and CH₄ emissions are driven by distinct sets of meteorological and soil environmental controls, with the latter showing considerable variations across different microforms (i.e., hummocks, lawns, hollows). Specifically, GPP mainly depends on green biomass and photosynthetic active radiation (PAR), and indirectly on variations in temperature, nutrient availability, soil moisture and soil-oxygen (O₂). Rewetting-induced increases in soil water saturation may change plant composition over time from shrub dominated communities towards wet-adapted species, such as *Sphagnum*, which may affect GPP (Crevey et al., 2020). It is further noteworthy that the components of Reco, i.e., Ra and Rh, are regulated by separate controls. Ra on the one hand commonly represents a relatively stable portion relative to plant production (Järveoja et al., 2018). Rh on the other hand is primarily controlled by substrate supply to microbial communities, with their activity further regulated by oxygen supply and peat temperature. However, rewetting-induced changes in vegetation dynamics may also affect Rh via altered substrate supply in the long-term (Lin et al., 2018). Overall, the net effect of rewetting-induced changes in GPP and Reco components on NEE is complex, as these flux components may respond similarly or differently to changes in various environmental conditions. Furthermore, CH₄ is produced by methanogenic bacteria in the anaerobic subsoil (Hanson and Hanson, 1996; Yvon-Durocher et al., 2014). However, CH₄ is also oxidized to CO₂ in the upper oxic peat layer above the water table level (Raghoebarsing et al., 2005). A rise in WTL following the rewetting of drained peatlands therefore commonly leads to increased CH₄ emissions (Komulainen et al., 1998). Furthermore, rewetting-induced changes in plant productivity may alter substrate supply to methanogens, while changes in plant composition towards aerenchymous species may enhance CH₄ emissions by providing direct plant-mediated pathways to the atmosphere (Komulainen et al., 1998; Ström et al., 2005). Thus, there is a need to disentangle effects from changes in both vegetation and environment to better understand the response of CH₄ emissions to peatland rewetting.

Drainage ditches affect peatland properties through its effective drainage distance, which can reach up to 200 m from the ditch (Landry and Rochefort, 2012). The drainage distance effect defines the area, where the WTL is lowered and oxygen reaches deeper peat layers, thereby causing enhanced peat decomposition (Kasimir et al., 2018). Increased peat mineralization commonly leads to a change in peat physical properties, such as bulk density, hydraulic and thermal conductivity (Minkinen and Laine, 2006). In theory, drainage effects are commonly expected to be higher closer to the ditch and weaken with increasing distance (Bring et al., 2022; Palviainen et al., 2024). Nevertheless, there is a lack of empirical in-situ data on the spatial variation of vegetation and subsequent C fluxes in relation to ditch distance.

This study investigated forest-floor CO₂ and CH₄ fluxes and their biotic and abiotic controls for one year prior and two years following rewetting of a minerogenic peatland forest in northern Sweden. The main objectives were to investigate how rewetting affects i) the seasonal variations and magnitudes of the separate C cycle component fluxes (i.e., production and respiration fluxes, as well as CH₄ emissions), ii) the sensitivity of these component fluxes to biotic and abiotic controls, and iii) the spatial variation of CO₂ and CH₄ fluxes in response to ditch distance during drained and rewetted conditions.

2. Material and methods

2.1. Site description and experimental design

2.1.1. Site description

The study was conducted at the peatland rewetting site (22.3 ha) within the Trollberget Experimental Area (TEA, Laudon et al., 2023) located approximately 50 km north-west of Umeå, Västerbotten, Sweden (64° 10' 51.61" N, 19° 50' 14.06" E). The long-term (1991–2020) mean annual temperature for the region is 2.4 °C, with mean monthly air temperatures ranging from −13.5°C to +16.3 in January and July, respectively. Total annual precipitation is on average 631 mm yr⁻¹ of which 35–50% falls as snow (Svartberget Research Station, 2025). Snow cover lasts on average for 167 days from late October to early May (Laudon et al., 2023).

Prior to drainage, the study area was a sparsely treed minerogenic, oligotrophic mire, exhibiting characteristics of a flark fen, with wetter depressions (flarks) alternating with drier hummocks (strings). The site was drained in the years following 1910 when the legal application for ditching was formally documented. The drainage activities were carried out by hand, leading to the formation of a sparse drainage network consisting of a main ditch (about 5 m wide and 2 m deep) running east-west through the centre of the site, along with a few smaller auxiliary ditches (about 1 m wide and 1 m deep). After the drainage the formerly sparsely treed areas, being located mainly in the north and east of the peatland, developed into a low-productive peatland forest (2.6 m³ ha⁻¹), dominated by Scots pine (*Pinus sylvestris* L.) as was evident by historic maps in 1924 (Norstedt et al., 2021). The ditch network was not maintained in the years following drainage, resulting in a decline in drainage function due to peat infilling and vegetation growth. The site was rewetted in November 2020 using a 20-ton crawling excavator following conventional authority-defined methods. The activities involved removing the sparse tree cover and filling of the ditches with on-site peat and the harvested tree logs. The biomass of trees and stumps was left on the peatland.

The vegetation community present at the time of the study was dominated by the residual plant community that persisted following drainage. Specifically, this included vascular plants, mainly shrubs, such as bog bilberry (*Vaccinium uliginosum* L.), bog cranberry (*V. oxycoccos* L.), black crowberry (*Empetrum nigrum* L.), common heather (*Calluna vulgaris* L. (Hull)) and bog rosemary (*Andromeda polifolia* L.), mosses, particularly *Sphagnum* spp., and graminoids, such as cottongrass (*Eriophorum vaginatum* L.). The site also featured a few areas of bare peat and open water.

The average peat depth is 241 cm (range from 22 to 599 cm; N = 190), with an average C/N ratio of 42.7 in the topsoil (0–30 cm). Bulk density in the top soil ranges from 0.026 to 0.195 g cm⁻³, averaging at 0.092 g cm⁻³.

2.1.2. Experimental design

The study design follows a before-after treatment approach. Four transects, each consisting of 6 sampling plots, were placed perpendicular to the main drainage ditch with sampling locations at 5, 25 and 50 m distance from each side of the ditch (Fig. 1).

2.2. Greenhouse gas flux measurements

The separate C cycle component fluxes (i.e., NEE, GPP, Rh, Ra, and CH₄) were measured along the two eastern transects, where each sampling plot was divided into two subplots, including a natural and a vegetation-removal subplot. The natural subplot resembled representative vegetation cover and species composition for the surrounding sample plot area. The vegetation-removal plot was established in autumn 2018 by clipping all vascular plants and green moss parts, including trenching to exclude lateral roots. Newly emerging vegetation was continuously removed from these experimental subplots. The

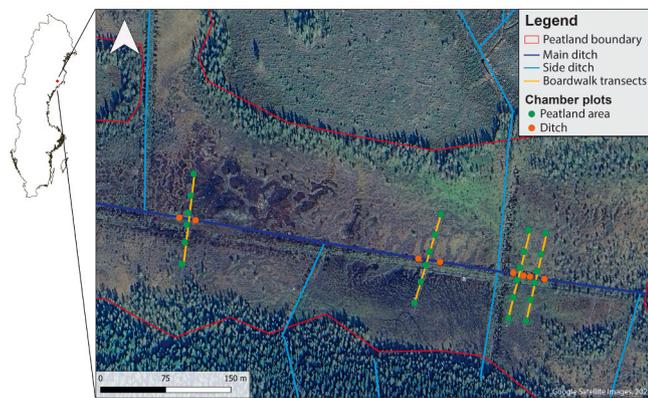


Fig. 1. Experimental design for chamber flux measurements at the Trollberget rewetted peatland. Yellow lines represent wooden boardwalk transects. Green dots denote the sampling plots on the peatland area, with 3 locations at either side of the main ditch at distances of 5, 25 and 50 m from the main ditch. Red dots denote the 8 sampling plots inside of the main ditch.

remaining two western transects featured only natural subplots to determine NEE, GPP, Reco and CH₄ fluxes. The latter were added in 2020 to complement an original set of transects (with 40 m spacing) established in 2018 in previous work focusing on the eastern side of the study area to further extend the coverage of spatial variations for this study. At each subplot, a square aluminium frame of 48.5 × 48.5 cm was permanently installed to a depth of about 10 cm to facilitate C flux measurements which were conducted bi-weekly during the frost-free season (mid-May to mid-October) using the closed-chamber method (Hutchinson and Livingston, 1993). Fluxes were measured using a custom-made transparent chamber (light transmission rate 81%, 47 × 47.5 × 25 cm) made of acrylic Plexiglas® (Röhme GmbH, Weiterstadt, Hessen, Germany). The chamber was also equipped with a HOBO pendant logger (MX2202, Licor, Bourne, MA, USA) to measure photosynthetic active radiation (PAR) and temperature in- and outside the chamber headspace. The effective chamber headspace was estimated by accounting for variations in surface elevation height relative to the top of measurement frame, which occurred due to changes in microtopography and water table level (i.e., in the case of flooding). During each measurement, the chamber was placed for 3 min onto the frame, and the concentration of CO₂ and CH₄ in the chamber headspace were measured with a portable gas analyser (Gas Scouter TM G4301, Picarro, Santa Clara, CA, USA). Net forest-floor CO₂ exchange (NE_{ff}) and methane (CH₄) fluxes were measured under ambient light, while for the measurements of forest-floor respiration (R_{ff}) and heterotrophic respiration (Rh), the chamber was covered with an opaque cloth to ensure dark conditions. Gross primary production (GPP_{ff}) and autotrophic respiration (Ra_{ff}) of the forest-floor vegetation were calculated using a mass balance approach, with $GPP_{ff} = NE_{ff} - R_{ff}$ and $Ra_{ff} = R_{ff} - Rh$.

To obtain flux rates, the slope of the change in headspace concentrations over time (dC/dt ; ppm s⁻¹) was determined by simple linear regression. Flux rates were then calculated based on dC/dt , applying the ideal gas law (Eq. 1):

$$F = \frac{dC}{dt} \times \frac{V \times p}{R \times T_a \times A} \quad (1)$$

where F is the measured flux (μmol m⁻² s⁻¹), dC/dt is concentration change over time (ppm s⁻¹), V is the effective chamber headspace volume (m³), p is the atmospheric pressure (assumed to be constant at 101,325 Pa), R is the universal gas constant of 8.3143 (m³ Pa K⁻¹ mol⁻¹), T_a is the mean ambient air temperature (K) during the measurement, and A is the area inside the frame (m²).

Poor-quality flux data were filtered out by applying thresholds in the root-mean-square error (RMSE) and r^2 . Specifically, fluxes were filtered

out based on the following criteria: CO₂ $r^2 < 0.9$ and RMSE > 0.5 and for CH₄ if, $r^2 < 0.9$ and RMSE > 0.02. This led to a removal of 9.0% and 4.4% of CO₂ and CH₄ flux data, respectively. In this study, we follow the atmospheric sign convention, where positive and negative values indicate emissions from and uptake by the ecosystem, respectively.

2.3. Environmental variables

WTL was continuously measured with automated loggers (Levelogger 5 Junior; Solinst Canada Ltd., Georgetown, ON, Canada) beside each flux subplot in a PCV groundwater tube (Ø = 32 mm external and 26 mm inside, 125 cm long with 3 mm holes every 2.5 cm) and manually every second measurement round in the same tube, which was inserted to a depth of 1 m into peat next to the frames. These manual WTL data were used to calibrate the automated WTL data. Soil temperatures at 5 cm and 10 cm depth (Ts₅ and Ts₁₀, respectively) were also recorded manually next to the frames during each flux measurement using a digital thermometer (Sunartis). Air temperature (shaded, T_a) was measured using a HOBO pendant logger (MX2203). Meteorological data, such as precipitation and mean temperatures were recorded at the nearby (i.e., 7.7 km) climate station Svartberget-Hygget (64°14'37.68"N, 19°46'2.64"E, Svartberget Research Station, 2025).

In 2020, peat cores to a depth of 55 cm were taken at all plot locations using a custom-made stainless rectangular soil corer (inner dimensions 8 × 8.4 cm). For each 5 cm section of these cores, peat physiochemical properties were determined including bulk density (BD), total carbon (TC) and total nitrogen (TN). Bulk density samples were oven dried at 60°C until constant weight and cooled in a desiccator (Nalgene) before their dry weight was measured. Soil samples for the chemical analysis for TC and TN were ground, and oven dried at 60°C until constant weight and subsamples were then filled into small tin cups for elemental analysis (Isotope Ratio Mass Spectrometry system (Thermo Fisher Scientific)). The resulting data of 5 cm intervals were averaged for the top 20 cm of the peat profile.

2.4. Vegetation and microforms

Vegetation biomass and species composition of the forest-floor were determined in summer 2020 (pre-rewetting) and in summer 2024 (post-rewetting). Destructive sampling of vascular biomass was conducted using a 0.25 × 0.25 m frame in 3 different locations around each chamber location, representing the species composition within the chamber frame. Mosses were sampled in the upper 2 cm from a representative quarter of the vegetation frame. All species were categorized into the following plant functional types (PFT): graminoids, shrubs and peat mosses (*Sphagnum* spp.). The biomass was separated into brown and green biomass before oven-drying the samples at 65°C for 48 h before weighting. Vegetation biomass in 2022 was then estimated by linear interpolation between 2020 and 2024.

In addition, overhead images of the vegetation inside the frames were taken after each flux measurement to calculate the vegetation greenness index following Peichl et al. (2015) (Eq. 2).

$$gcc = \frac{G}{(R + G + B)} \quad (2)$$

where gcc is the greenness index (green chromatic coordinate) of the region of interest in each image (i.e., the area inside the chamber frame), R, G and B are the red, green and blue Digital Numbers (0–255).

At each flux frame location, the microform was determined based on visual assessment of the dominant vegetation and the measured mean growing season WTL in 2020 (following Euroala and Huttunen, 2006; Noumonvi et al., 2025). Hummocks were defined as areas with a mean growing season WTL of –50 to –20 cm and were dominated by shrubs (e.g., *Calluna vulgaris* L. and *Empetrum nigrum* L.). Lawns were defined by a mean WTL of –20 to –5 cm and wetter-adapted vegetation, including

graminoids (e.g., *Eriophorum vaginatum* L.), dwarf shrubs (e.g., *Andromeda polifolia* L. and *Vaccinium oxycoccos*) and *Sphagnum* spp. Hollows were defined by a mean WTL of > -5 cm and were dominated by *Sphagnum* spp., sparse graminoid vegetation or areas of bare peat.

2.5. Statistical analysis

Given the hierarchical structure of the flux data (i.e., repeated measurements along fixed transects at defined ditch distances), we applied Generalized Linear Mixed Models (GLMM) with repeated measures to test for significance of temporal (rewetting) and spatial (ditch distance) treatment effects on the C fluxes (i.e., NE_{ff} , GPP_{ff} , R_{ff} , Ra_{ff} , Rh and CH_4) and environmental variables (i.e., Ts_5 , Ts_{10} , WTL , gcc and PFTs). GLMMs can accommodate various data distributions and are well suited to handling non-random, hierarchical and non-independent data structures (Schielzeth et al., 2020). Within each PFT, differences in vegetation biomass between years (pre- and post-rewetting) and among different ditch distances were evaluated using a Wilcoxon signed-rank test.

The following GLMM model was applied (Eq. 3):

$$y_{ij} = \beta_0 + T + D_j + DT_j + F + S_i + \varepsilon_i \quad (3)$$

where y denotes the gas flux or environmental variable for sampling occasion i , β_0 denotes the mean of the flux or environmental variable, T denotes the sampling year and thus rewetting treatment effect, D_j denotes the fixed effect of distance to ditch j , DT_j denotes the interaction between the effects of rewetting and distance to ditch j , F denotes the fixed effect of transect to control for the hierarchical data structure, S_i denotes the fixed effect of sampling occasion i expressed as day of year (doy) and ε_i denotes the random error of the plot location for sampling occasion i . Statistical results from the GLMMs were considered significant at $p < 0.05$. Gaussian and Gamma Log Link functions were used depending on data distribution. Standard errors ($\pm SE$) of sample averages were used as a measure of uncertainty. Matlab R2022b was used for flux calculations and R for all further analysis. GLMMs were developed using the “glmmTMB” package (Brooks et al., 2017).

3. Results

3.1. Environmental conditions

The annual mean T_a at the nearby Hygget-Svartberget climate station for the studied years 2020, 2021 and 2022 was 4.1, 2.2 and 3.2°C, respectively, being above, below and similar to the long-term normal (3.0°C; 1991–2020), respectively. The annual PPT in 2020, 2021 and 2022 was 795, 766 and 639 mm, respectively, being higher in 2020 and 2021 and similar in 2022 compared to the long-term normal (634 mm).

The daytime T_a during the flux measurement campaigns in 2020 was higher in June, but lower in July compared to 2021 and 2022 (Fig. 2a). Daytime soil temperature at 5 cm depth (Ts_5) on the flux measurement days peaked at 22.8°C in June 2020, at 20.5°C in July 2021 and at 22.2°C in June 2022 (Fig. 2a). The growing season means of T_a were significantly lower in 2022 compared to 2020, while Ts_5 was significantly warmer in 2022, compared to 2020 (Table S2). The temporal patterns and magnitudes of PAR during the measurement campaigns were similar among the three years (Fig. 2b), however, the growing season mean of the second rewetting year was significantly higher compared to the pre-rewetting year (Table S2). The WTL on the flux measurement days ranged from -42.7 to -13.0 cm in the pre-rewetting year, while in the post-rewetting years, the range was -25.1 to -4.0 cm and -18.0 to -7.4 cm, respectively (Fig. 2c). The mean growing season WTL increased significantly from -23 cm in 2020 to -12.2 cm in 2021, with no significant difference observed between 2021 and 2022 (-10.5 cm, Table S2). Following rewetting, peak season mean gcc increased by 61% in 2022 relative to 2020 (Fig. 2d).

3.2. Seasonal variation in peatland forest-floor C fluxes

The seasonal variation (i.e., amplitude) of daytime NE_{ff} and GPP_{ff} increased over the 3 study years, while that of R_{ff} remained at similar levels (Fig. 3a). Maximum daytime net CO_2 uptake increased from -66 mg C m $^{-2}$ h $^{-1}$ in 2020 to -109 mg C m $^{-2}$ h $^{-1}$ in 2021 and to -150 mg C m $^{-2}$ h $^{-1}$ in 2022. The mean daytime net CO_2 uptake averaged across the growing season increased significantly from -30 ± 5 mg C m $^{-2}$ h $^{-1}$ in the pre-rewetting year to -62 ± 5 mg C m $^{-2}$ h $^{-1}$ and -90 ± 6 mg C m $^{-2}$ h $^{-1}$ in the post-rewetting years 2021 and 2022, respectively (Table 1). Maximum GPP_{ff} increased from -222 mg C m $^{-2}$ h $^{-1}$ in 2020 to -251 mg C m $^{-2}$ h $^{-1}$ in 2021 and to -271 mg C m $^{-2}$ h $^{-1}$

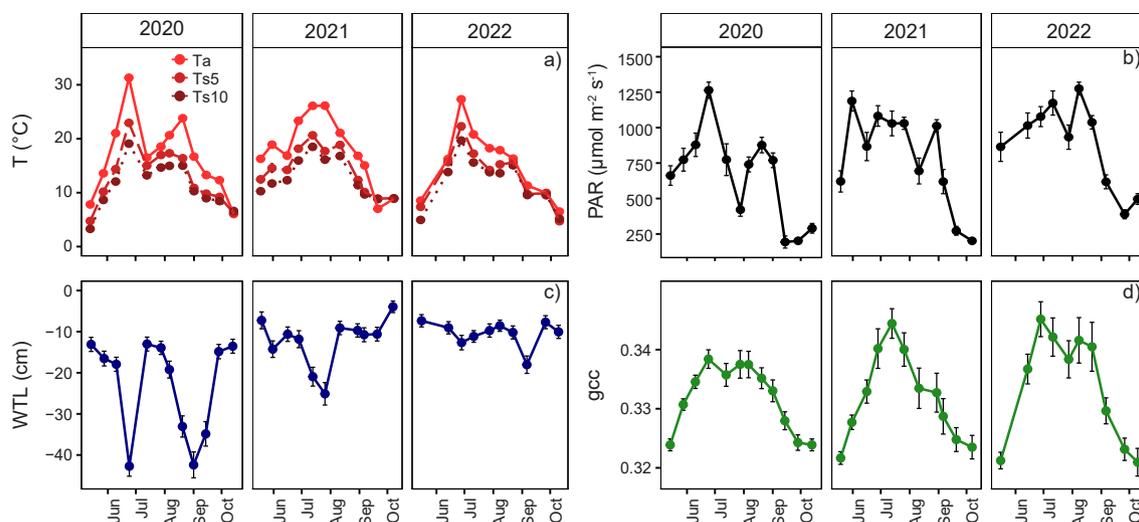


Fig. 2. Mean environmental conditions during the flux measurement campaigns, including a) temperature (T) of the air (T_a) and soil at depth of 5 cm (Ts_5) and 10 cm (Ts_{10}), b) photosynthetically active radiation (PAR), c) water table level (WTL) and d) vegetation greenness index (i.e., green chromatic coordinate, gcc) during the drained (2020) and rewetted years (2021–2022). Symbols denote means of each sampling occasion with error bars indicating ± 1 standard error (SE) across all plots ($N = 24$).

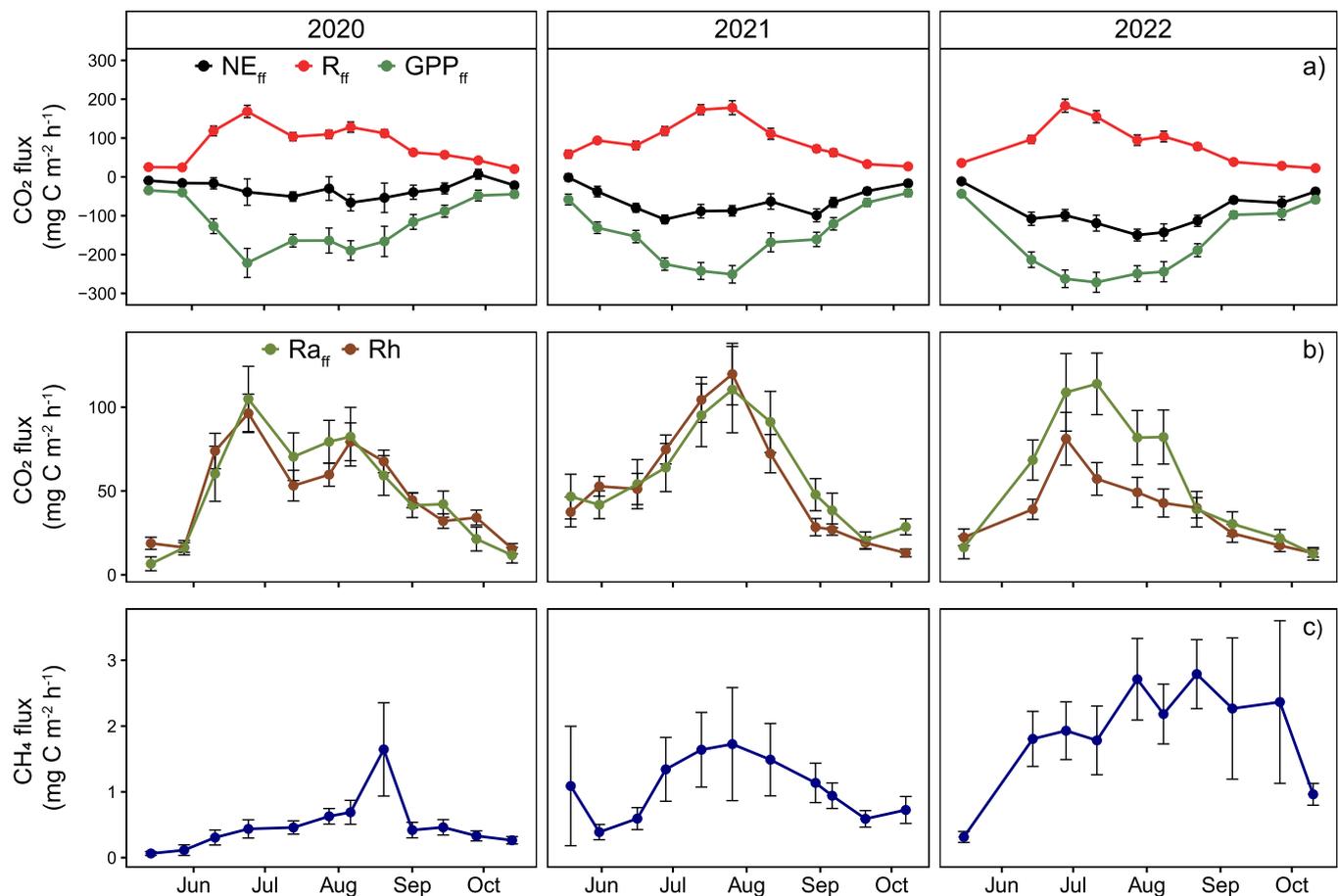


Fig. 3. Seasonal variations in peatland forest-floor (ff) fluxes, including a) daytime net CO₂ exchange (NE_{ff}), gross primary production (GPP_{ff}) and respiration (R_{ff}), b) autotrophic (Ra_{ff}) and heterotrophic (Rh) respiration and c) methane (CH₄) emissions during the pre- (2020) and post-rewetting period (2021–2022). Symbols denote means of each sampling occasion, with error bars indicating \pm standard error (SE; N = 24).

Table 1

Growing season means \pm standard error (SE) (mg C m⁻² h⁻¹) of forest-floor (ff) fluxes, including measured daytime net CO₂ exchange (NE_{ff}), gross primary production (GPP_{ff}), respiration (R_{ff}) with its individual heterotrophic (Rh) and autotrophic (Ra_{ff}) components as well as methane (CH₄) emissions during the pre- (2020) and post-rewetting years (2021–2022). N refers to the sample size of each model. Asterisks indicate significant differences between the pre- and post-rewetting years based on the Generalized Linear Mixed Model, with *p*-levels denoted as * < 0.05, ** < 0.01, *** < 0.001.

	N	Pre-rewetting (2020)	Post-rewetting (2021)	Post-rewetting (2022)
<i>Peatland forest-floor</i>				
NE _{ff}	670	-30 \pm 5	-62 \pm 5***	-90 \pm 5***
GPP _{ff}	651	-113 \pm 7	-147 \pm 6*	-172 \pm 7***
R _{ff}	762	82 \pm 4	92 \pm 4	85 \pm 5
Ra _{ff}	323	49 \pm 5	59 \pm 6	60 \pm 6
Rh	357	49 \pm 3	56 \pm 4	39 \pm 3***
CH ₄	737	0.49 \pm 0.07	1.1 \pm 0.2***	1.9 \pm 0.2***

in 2022 (Fig. 3a). Meanwhile, the growing season mean of GPP_{ff} increased significantly from -113 \pm 7 mg C m⁻² h⁻¹ in the pre-rewetting year to -147 \pm 6 mg C m⁻² h⁻¹ and -172 \pm 7 mg C m⁻² h⁻¹ in the post-rewetting years 2021 and 2022, respectively (Table 1). Daytime R_{ff} peaked at 168 mg C m⁻² h⁻¹ in late June 2020, at 178 mg C m⁻² h⁻¹ in late July 2021 and at 183 mg C m⁻² h⁻¹ in late June 2022 (Fig. 3a). The growing season means of daytime R_{ff} were not significantly different between 2020 and 2022. However, R_{ff} was significantly higher in 2021 (92 mg C m⁻² h⁻¹) than in 2022 (85 mg C m⁻² h⁻¹).

The seasonal variations in Rh and Ra_{ff} followed a similar pattern in

2020 and 2021 and differed only in the second post-rewetting year, in which Rh decreased whereas Ra_{ff} remained at a level similar to that of 2021 (Fig. 3b). Daytime Rh peaked at 96 mg C m⁻² h⁻¹ in 2020, at 120 mg C m⁻² h⁻¹ in 2021 and at 81 mg C m⁻² h⁻¹ in 2022. The growing season means of daytime Rh did not change significantly from the pre-rewetting year 2020 to first post-rewetting year 2021, however, decreased significantly from 2021 to 2022 (Table 1). Maximum daytime Ra_{ff} was 105 mg C m⁻² h⁻¹ in 2020, 111 mg C m⁻² h⁻¹ in 2021 and 114 mg C m⁻² h⁻¹ in 2022 (Fig. 3b). The growing season mean of daytime Ra_{ff} did not change significantly between the years (Table 1). As a result of the diverging responses of Ra_{ff} and Rh to rewetting, their ratio (i.e., Ra_{ff}:Rh) increased from 0.99 in 2020 to 1.05 and 1.51 in 2021 and 2022, respectively.

Growing season CH₄ emissions peaked at 1.7 mg C m⁻² h⁻¹ in 2020, at 1.7 mg C m⁻² h⁻¹ in late July 2021 and at 2.8 mg C m⁻² h⁻¹ in late August 2022 (Fig. 3c). The growing season mean of daytime CH₄ emissions increased significantly from 0.49 \pm 0.07 mg C m⁻² h⁻¹ in 2020 to 1.1 \pm 0.2 mg C m⁻² h⁻¹ in 2021 and 1.9 \pm 0.2 mg C m⁻² h⁻¹ in 2022, being more than 3.5 times higher in the second post-rewetting year compared to the pre-rewetting year (Table 1).

3.3. Ditch distance effects on environmental variables and C fluxes in drained and rewetted peatland

3.3.1. Environmental variables

In both the pre-rewetting year 2020 and the second post-rewetting year 2022, *Sphagnum* biomass was significantly lower at 5 m compared to 25 and 50 m distance from the ditch (Fig. 4a). Graminoid

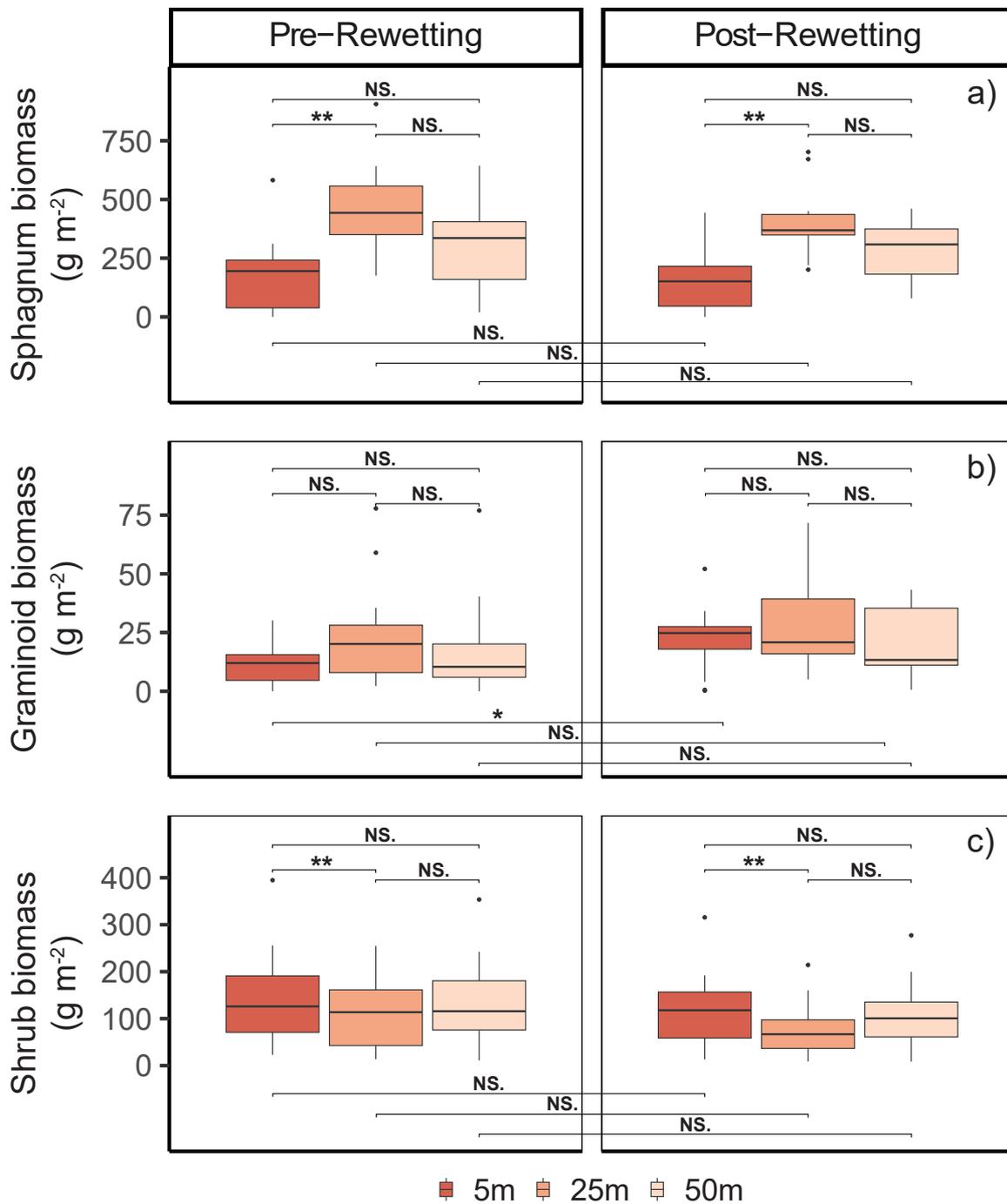


Fig. 4. Biomass for the key plant functional types of a) *Sphagnum* mosses, b) graminoids and c) shrubs at 5, 25 and 50 m from the main ditch during pre- (2020) and post-rewetting (2022), N = 144. The horizontal black line in the box signifies the median of the distribution, whiskers show the minimum and maximum datapoints, black dots signify outliers defined as higher or lower of 1.5 times of the interquartile range (range of box or the difference between 75th and 25th percentile). Asterisks indicate significant differences, at p-levels * < 0.05, ** < 0.01, *** < 0.001, NS. = not significant.

biomass increased significantly at the 5 m ditch distance from 12 to 23 g m⁻² between 2020 and 2022, respectively, but remained similar at the 25 and 50 m distances (Fig. 4b). Shrub biomass at the 25 m distance decreased (from 113 to 76 g m⁻²), although the change was not statistically significant (p = 0.23), and remained similar at the 5 and 50 m distances (Fig. 4c).

No significant differences in growing season PAR were noted among the different ditch distances, however, PAR was significantly higher at all ditch distances in 2022 compared to 2020 (Fig. 5a). In the pre-rewetting year, mean growing season WTL was significantly higher at

25 m compared to 50 m ditch distance, but not different from 5 m (Fig. 5b). In both post-rewetting years, WTL was also significantly higher at 25 m compared to 50 m, however not different from 5 m. The largest absolute change between 2020 and 2022 was observed at 5 m distance, where WTL increased by 13.3 cm, compared to 12.0 cm and 12.4 cm at 25 and 50 m distance, respectively (Table S3). No significant effects of ditch distance were noted for growing season gcc and soil temperature, however, soil temperature increased significantly at 50 m between 2020 and 2022 (Table S3).

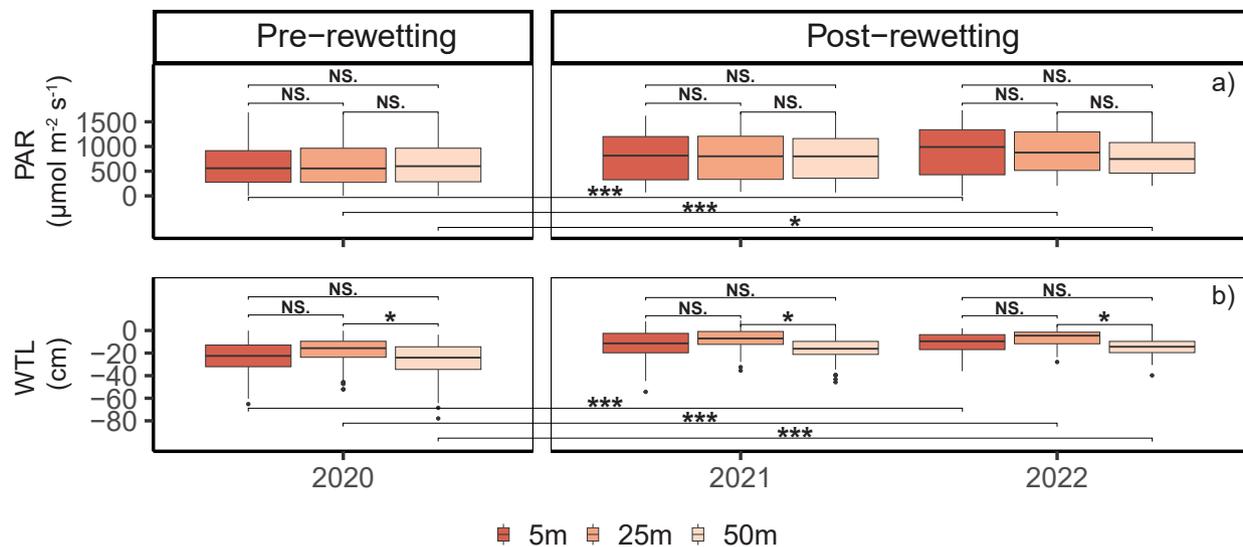


Fig. 5. Spatial variation of environmental conditions measured in relation to distance from ditch, including a) photosynthetically active radiation (PAR), b) water table level (WTL) at 5, 25 and 50 m from the main ditch during pre- (2020; $N = 288$) and post-rewetting years (2021 and 2022; $N = 264$ and 240 , respectively). Statistical significance depicts mixed model results for ditch distance within year and ditch distance across years. Asterisks indicate significant differences at p -levels * < 0.05 , ** < 0.01 , *** < 0.001 , NS. = not significant.

3.3.2. Carbon fluxes

The spatial variations in mean growing season NE_{ff} did not show any consistent gradient in relation to ditch distance (Fig. 6a). In the pre-rewetting year, the daytime net CO_2 uptake was significantly lower (i. e., less negative) at the 5 m distance compared to the 25 m distance, whereas NE_{ff} at the 50 m distance was not significantly different from the other locations (Fig. 6a; Table S1). In the post-rewetting years, NE_{ff} did not significantly differ among any of the three distances. Relative to the pre-rewetting year, the daytime net CO_2 uptake was significantly greater at 5 and 50 m in the first post-rewetting year and continued to significantly increase from the first to the second post-rewetting year for all ditch distances. The increase between 2020 and 2022 at the 5 m distance ($95 \text{ mg C m}^{-2} \text{ h}^{-1}$) was more than two times higher compared to the 25 and 50 m distances (36 and $48 \text{ mg C m}^{-2} \text{ h}^{-1}$, respectively). The difference in the net CO_2 uptake between 2020 and 2022 was just below the significance level ($p = 0.056$) (Figure S2a).

Similar to NE_{ff} , the spatial variations in GPP_{ff} did not exhibit a consistent gradient in relation to ditch distance (Fig. 6b). In the pre- and post-rewetting years GPP_{ff} was not significantly different among any of the ditch distances. Compared to the pre-rewetting year 2020, GPP_{ff} at 5 and 50 m was significantly greater in 2022 and 2021, respectively. The GPP_{ff} difference between 2020 and 2022 was significantly greater in hummocks compared to lawns (Figure S2b).

R_{ff} and Ra_{ff} did not show any significant spatial gradient in the pre-rewetting year, however, R_h at 5 m was significantly higher than at 25 m in 2020 (Fig. 6c, d, e). In the post-rewetting years, R_{ff} was significantly lower at the 25 m distance compared to 50 m in 2021, while in 2022, R_{ff} was significantly lower at 25 m than at 5 m distance. Among all ditch distances, R_{ff} decreased only at 25 m from 2020 to 2022. Ra_{ff} at 5 m was significantly higher than at 25 and 50 m in 2022. Relative to pre-rewetting, Ra_{ff} increased significantly at 5 m distance, while decreasing significantly at 25 m. R_h was significantly lower at 25 m compared to 5 m, but not to 50 m in 2020. In 2021 and 2022, R_h at 25 m was lower than at 5 and 50 m ditch distances. R_h decreased significantly at 5 m and 25 m distances between 2020 and 2022. None of the respiration flux changes between 2020 and 2022 differed significantly between hummocks and lawns (Figure S2c-e).

CH_4 emissions during pre-rewetting were highest at 25 m and significantly different from 50 m, however, without showing a clear

gradient with increasing ditch distance. In the post-rewetting years, CH_4 emissions were highest at 5 and 25 m and significantly different from 50 m. CH_4 emissions at all ditch distances increased significantly between 2020 and 2022 (Fig. 6e). Furthermore, the flux change of CH_4 between 2020 and 2022 was not significantly different between hummocks and lawns (Figure S2f).

3.4. Environmental controls on the spatial variations of carbon fluxes

In the pre-rewetting year, NE_{ff} and GPP_{ff} were negatively correlated to *Sphagnum* biomass ($p < 0.01$) and gcc ($p < 0.05$), while GPP_{ff} was additionally negatively correlated to $Ts5$ and positively correlated to WTL ($p < 0.05$, Table 2). R_{ff} was positively correlated to $Ts5$ and shrub biomass ($p < 0.001$). Further, Ra_{ff} showed negative correlations to graminoids biomass ($p < 0.01$), while exhibiting a positive correlation to gcc ($p < 0.01$) and bulk density ($p < 0.05$). R_h was positively correlated with $Ts5$ ($p < 0.001$). CH_4 fluxes were positively correlated to graminoid biomass ($p < 0.001$) and negatively correlated to BD and shrub biomass ($p < 0.01$).

In the second post-rewetting year (2022), NE_{ff} and GPP_{ff} were negatively correlated to gcc ($p < 0.001$) and shrub biomass ($p < 0.05$ for NE_{ff} and $p < 0.001$ for GPP_{ff}). However, compared to the pre-rewetting year, neither flux remained correlated to *Sphagnum* biomass (Table 2). R_{ff} continued to be positively correlated to $Ts5$ ($p < 0.001$) and shrub biomass ($p < 0.001$), while additionally been positively correlated to gcc ($p < 0.001$). Ra_{ff} in the second-year post rewetting remained positively correlated to gcc ($p < 0.01$), and negatively to graminoids ($p < 0.05$), while the relationship to BD was no longer significant. R_h continued to be positively correlated to $Ts5$ ($p < 0.05$) and was additionally negatively correlated to WTL ($p < 0.01$). CH_4 emissions were positively correlated to WTL ($p < 0.01$) and gcc ($p < 0.001$), while being negatively correlated to shrub biomass ($p < 0.01$).

4. Discussion

4.1. Initial effects of rewetting on the peatland carbon cycle component fluxes

The results from our study highlight that rewetting of a minerogenic peatland forest immediately modifies the spatial variations and

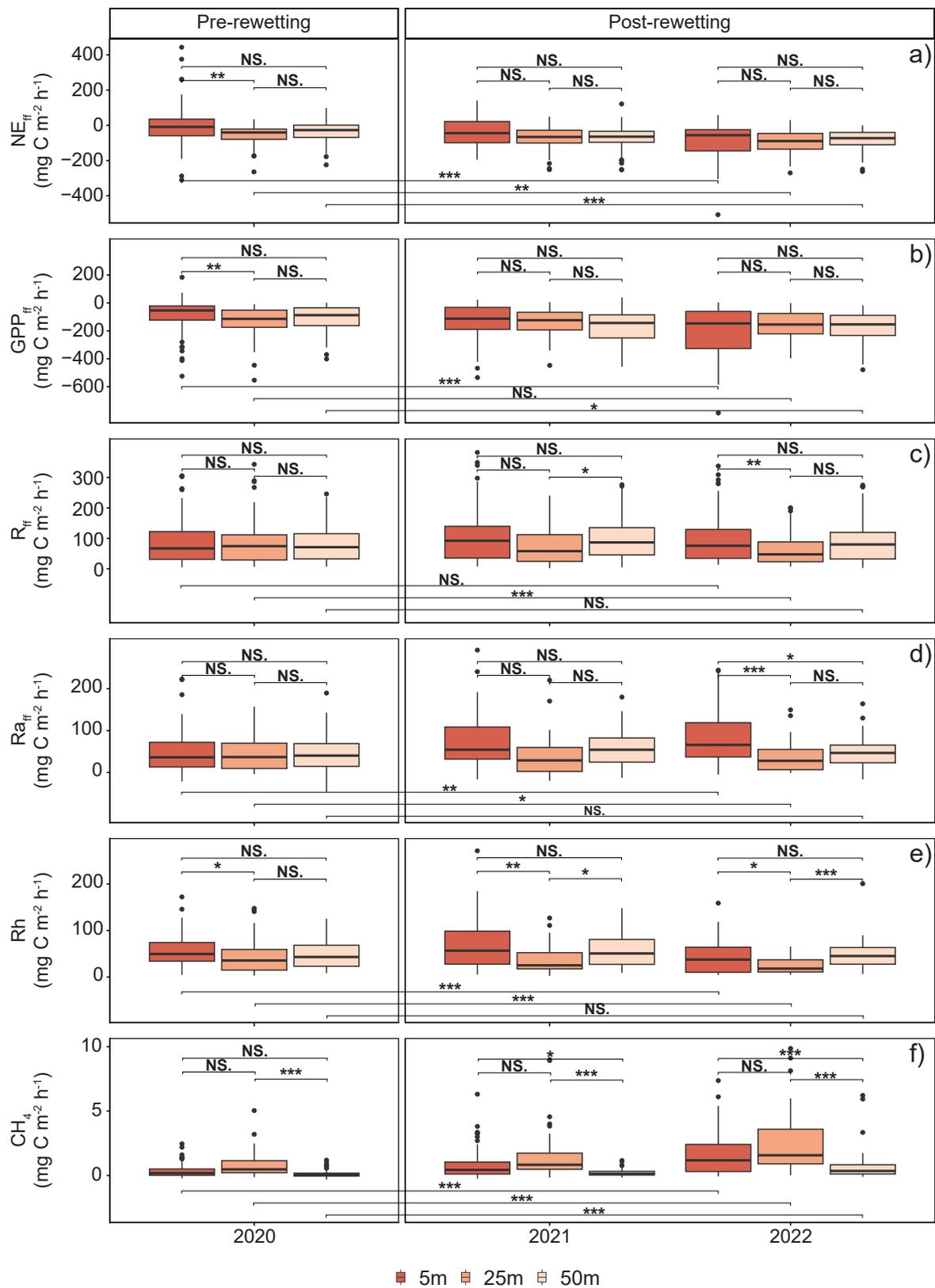


Fig. 6. Box plots for forest-floor (ff) fluxes, including a) daytime net CO₂ exchange (NE_{ff}), b) gross primary production (GPP_{ff}), c) respiration (R_{ff}), d) autotrophic respiration (Ra_{ff}), e) heterotrophic respiration (Rh) and f) methane (CH₄) emissions at 5, 25 and 50 m distances from the main ditch during pre- (2020; N = 288) and post-rewetting years (2021 and 2022; N = 264 and 240, respectively). The horizontal black line in the box signifies the median of the distribution, whiskers show the minimum and maximum datapoints, black dots signify outliers defined as higher or lower of 1.5 times of the interquartile range (range of box or the difference between 75th and 25th percentile). Statistical significance depicts mixed model results for ditch distance within year and ditch distance across years. Asterisks indicate significant differences, at p-levels * < 0.05, ** < 0.01, *** < 0.001, NS. = not significant.

Table 2

Generalized Linear Mixed Model results for environmental (biotic and abiotic) variables explaining the spatial variations in flux components in the pre-rewetting year (i.e., 2020) and in the second post-rewetting year (i.e., 2022). Flux components include forest-floor net CO₂ exchange (NE_{ff}), gross primary production (GPP_{ff}), respiration (R_{ff}) with its individual heterotrophic (Rh) and autotrophic (Ra_{ff}) components as well as methane (CH₄). Environmental variables include water table level (WTL), bulk density (BD), CN ratio (CN), soil temperature at the 5 cm depth (Ts5), vegetation greenness index (gcc) as well as biomass of *Sphagnum*, graminoids and shrubs. Temporal effects were controlled via day of year and spatial heterogeneity via Transect as fixed and plot ID as random effect. N refers to the sample size of each model. Asterisks indicate significance at *p*-levels * < 0.05, ** < 0.01, *** < 0.001, n.a. = not applicable since the variable was not considered as potential driver by the model; r²C = conditional coefficient of determination, r²M = marginal coefficient of determination. Plus sign (+) indicates positive and minus sign (–) negative relationships with the C fluxes, respectively. Note NE_{ff} and GPP_{ff} are negative due to atmospheric sign convention.

	Time	N	WTL	BD	CN	Ts5	gcc	Sphagnum	Graminoids	Shrubs	r ² C	r ² M
NE _{ff}	Pre-rewetting	235					–*	–*			0.54	0.27
	Post-rewetting	185					–***			–*	0.60	0.47
GPP _{ff}	Pre-rewetting	226	+*			–*	–**	–*			0.65	0.50
	Post-rewetting	180					–***			–***	†	0.67
R _{ff}	Pre-rewetting	269				+***				+***	0.76	0.71
	Post-rewetting	202				+***	+***			+***	0.87	0.74
Ra _{ff}	Pre-rewetting	118		+*			+**		–**		†	0.63
	Post-rewetting	90					+**		–*		0.73	0.57
Rh	Pre-rewetting	130				+***	n.a.	n.a.	n.a.	n.a.	0.67	0.54
	Post-rewetting	97	–**			+*	n.a.	n.a.	n.a.	n.a.	0.75	0.47
CH ₄	Pre-rewetting	274		–**					+***	–**	0.57	0.47
	Post-rewetting	190	+**				+***			–**	0.60	0.49

† Conditional r² could not be estimated since random variance was zero after incorporating fixed effects.

magnitudes of the individual C cycle component fluxes. Our key finding reveals a non-uniform spatial response of C fluxes to rewetting due to microtopographic feedbacks, which poses a challenge for predicting initial rewetting effects on the C cycle of heterogeneous peatlands.

4.1.1. Net CO₂ exchange

Specifically, we observed that the daytime net CO₂ uptake (NE_{ff}) increased on average by 3 times over the study period, which was driven by a 50% increase in forest-floor production (GPP_{ff}), whereas forest-floor respiration (R_{ff}) remained constant. This suggests an immediate and positive response of the vegetation to the improved growing conditions. The latter was mainly due to the increased WTL which likely facilitated enhanced photosynthetic CO₂ uptake by both vascular plants, primarily shrubs, and *Sphagnum* mosses during the driest summer periods. The enhanced vegetation growth was also reflected by the observed increase in the vegetation greenness index (i.e., gcc) in 2021. In addition, however, greater PAR during 2022 could partly explain the higher GPP_{ff} in the second rewetting year. Peak daytime net CO₂ uptake (–150 mg C m^{–2} h^{–1}) and GPP_{ff} (–271 mg C m^{–2} h^{–1}) at our study site were similar to a rewetted site in Southern Finland two years after rewetting (NEE –136 mg C m^{–2} h^{–1}, GPP –327 mg C m^{–2} h^{–1}; Tuittila et al., 1999). In contrast, our peak GPP estimates were higher than those in 3 different bogs (45 to 165 mg C m^{–2} h^{–1}) and one fen (64 mg C m^{–2} h^{–1}) in Estonia and Finland (Purre et al. 2019b). Furthermore, peak daytime net CO₂ uptake and GPP at our site were higher compared to peak rates of NEE (–42 to –14 mg C m^{–2} h^{–1}) and GPP (–23 to 98 mg C m^{–2} h^{–1}) reported for former peat extraction areas in Estonia that were restored using the moss layer transfer technique (Järveoja et al., 2016; Purre et al., 2019a). This difference is likely due to the presence of established ground vegetation at the time of rewetting a peatland forest, compared to the initial lack of vegetation in a rewetted peat extraction area. Altogether, this highlights the importance of vegetation as key control of the NEE response to rewetting.

Although R_{ff} appeared unaffected by rewetting, our results revealed a notable divergence in the responses of its component fluxes, with an increase of the Ra_{ff}:Rh ratio observed following rewetting. The small increase of Ra_{ff} is in line with the increase in GPP_{ff} occurring after rewetting, whereas Rh overall decreased likely in response to the elevated WTL and oxygen limitation (Frolking et al., 2001; Withing and Chanton, 2001; Järveoja et al., 2016). It is noteworthy that, relative to the considerable increase in GPP_{ff}, the increase in Ra_{ff} was modest in 2021 and decreased even to pre-rewetting levels in 2022. This is likely because tree root respiration contributing to Ra_{ff} during the

pre-rewetting year was eliminated following the tree harvest, thus counterbalancing the increase in Ra_{ff} from the ground vegetation. Furthermore, increased Rh from the additional decay and decomposition of these tree root remnants might also counterbalance the initial decrease of Rh via reduced peat decomposition. However, our experimental study design did not allow us to quantify this separate effect. It is further noteworthy that a clear decrease in Rh was only observed in the second rewetting year. Possibly, substantial reductions in WTL occurring during the warm summer of 2021 might have still provided sufficient aerobic conditions, thereby leading to a delayed response of Rh to the WTL increase. By 2022, however, Rh decreased below pre-rewetting levels. Overall, our results highlight the complex and partly counterbalancing responses of the peatland CO₂ component fluxes to rewetting.

4.1.2. CH₄ fluxes

Our results further demonstrate that the rise in WTL following rewetting caused an almost 4-fold increase in mean CH₄ emission rates. However, the observed CH₄ emission rates following rewetting (1.9 mg C m^{–2} h^{–1} in 2022) were still a magnitude lower compared to rates (11–23 mg C m^{–2} h^{–1}) reported from rewetted peat extraction areas in Estonia two years after rewetting (Järveoja et al., 2016). Compared to our site, peat extraction areas may exhibit greater amounts of labile organic matter, due to heavier decomposed peat, differences in vegetation composition and less methanotrophic bacteria due to a less developed oxic top-soil layer, which may explain the higher CH₄ fluxes (Järveoja et al., 2016). On the other hand, our rates were relatively similar to a rewetted fen (0.31 mg C m^{–2} h^{–1}) and bog (0.89 mg C m^{–2} h^{–1}) in Southern Finland two years after rewetting (Komulainen et al., 1998), other peatlands in Southern Finland 11–17 years after rewetting (1.6–2.1 mg C m^{–2} h^{–1}, Koskinen et al., 2016), and a restored fen in Canada 1 year after rewetting (1.6 mg C m^{–2} h^{–1}, Turmel-Courchesne et al., 2023). Overall, our results highlight the potential of enhanced CH₄ emissions to counterbalancing the positive climate mitigation effect from increased daytime net CO₂ uptake following rewetting, specifically when accounting for the larger warming potential of CH₄ relative to CO₂ (i.e., 28 times greater over a 100-year timeframe, IPCC, 2021).

4.2. Impact of rewetting on the spatial variations of environmental conditions, carbon fluxes and their interactions

An important aim of our study was to highlight the spatial variations of C fluxes after rewetting. A common notion is that drainage ditches create regular and thus predictable gradients in environmental

conditions (in particular for WTL) and thereby also in GHG fluxes (Landry and Rochefort, 2012; Laurén et al., 2021; Palviainen et al., 2024; He et al., 2025). Conversely, a spatial pattern in the response to rewetting via ditch-blocking may be expected with rewetting effects assumed to be greatest close to the ditch and to gradually decrease with increasing ditch distance. Our results contradict this theory by revealing more complex spatial patterns in environmental conditions and associated GHG fluxes, suggesting that ditch distance effects may be overruled by other factors, such as surface microforms, underlying topography, and nutrient distribution. For instance, rewetting increased the WTL significantly at all ditch distances, however, the response rates did not follow a linear gradient with increasing ditch distance. Similarly, neither changes in soil temperature nor vegetation properties showed linear gradients related to ditch distance, emphasizing the overall heterogeneous growing conditions across the peatland area. It is noteworthy that at the 5 m ditch distance, the increase in graminoid biomass corresponded to the largest WTL rise following rewetting. The concurrent reduction in shrub biomass at 25 m distance might further counterbalance the effects on the spatial patterns of total biomass and gcc. Overall, our results suggest that variations in microtopography and related environmental conditions rather than gradients of hydrological conductivity predetermined the response size of abiotic and biotic variables to rewetting.

The lack of spatial gradients in environmental conditions likely explain the non-linear spatial response noted also for NE_{ff} and its components. The largest increase in the daytime net CO_2 uptake at 5 m distance was likely caused by the largest WTL rise and increase in graminoid biomass. In comparison, the 25 m locations were more frequently located on lawns with higher WTL already during the drained years and higher net CO_2 uptake compared to 5 m, resulting in observed partial flooding and a reduction of shrub biomass following rewetting which may explain the smallest change in NE_{ff} at this distance. This is further supported by GPP_{ff} increasing at 5 and 50 m, while remaining similar at 25 m distance in the post-rewetting years. Furthermore, the changes in NE_{ff} and GPP_{ff} between 2020 and 2022 differed between hummocks and lawns, indicating a stronger increase in GPP_{ff} , and a tendency toward greater net CO_2 uptake, in hummocks compared to lawns. Similarly, Komulainen et al. (1999) found highest C uptake in hollows of a rewetted bog or plots with high *Eriophorum* spp. cover in a rewetted fen. Furthermore, the respiration components R_h and R_{ff} also showed the strongest rewetting response at 5 m distance, coinciding with high increases of WTL and graminoid biomass. Divergent responses of PFTs at the different distances might in the long-term also affect R_h due to changes in litter quality (Strack and Zuback, 2013). It is, however, noteworthy that the change in respiration fluxes between 2020 and 2022 did not differ between hummocks and lawns. Thus, while the strongest rewetting response of the CO_2 fluxes observed at the nearest ditch distance is in line with model theory (Palviainen et al., 2024), our results suggest that the spatial effects may be limited to the nearest area along the ditch without extending in predictable gradients further away across the peatland where effects from other factors, such as pre-rewetting vegetation composition or microtopography, may dominate.

Similar to NE_{ff} and its components, CH_4 fluxes did not show a consistent gradient with increasing ditch distance, neither prior nor following rewetting. However, the response rate of CH_4 emissions to rewetting decreased with increasing ditch distance. It is noteworthy that different microforms did not control this spatial pattern in the response rate of CH_4 emissions following rewetting. Observed CH_4 emission patterns were comparable to a rewetted nutrient-poor peatland in Finland 11–17 years after rewetting, where CH_4 emissions decreased with increasing distance from the ditch (Koskinen et al., 2016). Overall our study suggests that the spatial rewetting feedbacks may challenge the prediction of rewetting effects on the C cycle in heterogeneous peatlands based on ditch distance.

Our results further revealed a shift of abiotic towards biotic controls

of the spatial variations in GPP_{ff} which was primarily regulated by WTL and Ts_5 prior to rewetting but more closely correlated to shrub biomass and gcc following rewetting. Further GPP_{ff} , NE_{ff} and R_{ff} are throughout the study years controlled by gcc and R_{ff} in post-rewetting, which indicates a high importance of vegetation as control on plant production and respiration. *Sphagnum* biomass was important in explaining variations in GPP_{ff} , NE_{ff} only during pre-rewetting years, while such correlation disappeared following rewetting. This could be due to greater presence of *Sphagnum* species in wetter lawn locations during drained conditions, which at our site were mainly concentrated in areas around 15–40 m distance from the drainage ditch. Here, *Sphagnum* species might have substantially enhanced ecosystem productivity (Komulainen et al., 1999) relative to other locations, thereby causing spatial variations in C fluxes. Similar to the CO_2 fluxes, rewetting also triggered complex changes in the main drivers of CH_4 emissions. Further disentangling of the mechanisms explaining the changes within the driver network warrants future research, while being considered beyond the scope of this current study. Overall, our study highlights that the initial dynamics in soil environmental variables and vegetation development after rewetting, including shifts in the relative importance of PFTs, need to be carefully monitored and understood in detail as these strongly regulate the responses of the CO_2 flux components as well as CH_4 fluxes to rewetting.

4.3. Implications for predicting climate change mitigation effects of peatland rewetting

Peatlands are spatially heterogeneous ecosystems due to quasi-random variations in surface microtopography, peat depth, as well as water and associated nutrient flow patterns. Our ability to understand and predict the effects of these spatial variations on the separate C cycle component fluxes is limited but critical for assessing implications of rewetting for the net ecosystem C balance. The spatially non-uniform response of C fluxes to rewetting observed in our study poses a challenge for applying simplified emission factors (EF) developed by e.g. the IPCC to estimate initial climate benefits from rewetting, as commonly done in policy assessments (Laine et al., 2024). Since these EF assume homogenous conditions in both drained and rewetting states, as well as uniform responses of GHG fluxes across the entire ecosystem, our results indicate considerable potential for their estimates to differ from the actual response that integrates these various spatial effects. Therefore, it is important to identify if spatial effects, such as ditch distance or microforms are more important than temporal ones. Thus, we propose the development of refined, dynamic EF in time, e.g. initial years vs. 5, 10 or more years and space, e.g. for specific microforms (Ivanov et al., 2021) or vegetation communities (Couwenberg et al., 2011) as a way forward to a more realistic proxy-based prediction of rewetting effects on the peatland C balance. We caution, however, that the results from our local case study are limited in their spatial representation. Specifically, while our low-productive and nutrient-poor peatland forest site represents a typical feature of the boreal landscape in Sweden, it may not compare well to productive peatland forests with efficient drainage networks found in Finland and other parts of Fennoscandia. Our study is also limited in its temporal extent, capturing only responses during the early years following rewetting. Thus, there is a need for more empirical data across spatial gradients and based on long-term studies to reduce uncertainties and to develop spatially explicit and dynamic EFs for the boreal region.

The complexity in the spatially non-uniform responses of GHG fluxes to rewetting also poses a challenge for process-based model predictions (He et al., 2025). Specifically, models require systematic relationships on which spatial effects can be predicted (Palviainen et al., 2024; He et al., 2025). For instance, the peatland simulator SUSI predicts a distinct spatial gradient in the WTL response in relation to ditch distance (Palviainen et al., 2024). In contrast, the lack of clear spatial effects from both drained and rewetted (in-filled) ditches on C fluxes in our study

highlights the need to consider other factors as important model inputs for more accurately predicting spatial GHG flux dynamics in response to rewetting. For instance, utilizing data from ground penetrating radar and digital elevation models describing peat depth and surface topography, respectively, or improving our understanding on the coupling of biogeochemical ecosystem models to hydrological and microtopography models (e.g., [Noumonvi et al., 2025](#)) could help to better predict spatial patterns due to variations in vegetation, water and nutrients. Thus, our study highlights the need to account for spatial complexity in process-based models for improved predictions of rewetting effects on the peatland C cycle and associated climate impact.

5. Conclusions

In this study, we conducted 3 years of chamber-based flux measurements to investigate the effect of rewetting on the magnitudes and spatial variations of the individual C cycle component fluxes in a minerogenic peatland forest in boreal Sweden. Based on our findings, we conclude that the increase of the WTL may cause significant changes in vegetation composition and subsequently affect most C cycle components already during the initial two years following rewetting. Specifically, both daytime net CO₂ uptake as well as CH₄ emissions increased significantly after rewetting. The enhanced daytime net CO₂ uptake was driven by increased vegetation productivity, whereas initial changes in the respiration components were relatively limited. Our findings further demonstrate that while rewetting effects on C fluxes may be highest closest to the ditch, more complex spatial patterns across the remaining peatland area suggests that other factors, such as microtopography, rather than ditch distance explain the spatial variability of the C cycle components in both drained and rewetted conditions. In addition, our study revealed that shifts in the dominant abiotic and biotic drivers of the spatial variations in C fluxes may occur following rewetting. Altogether, these findings on the non-uniform spatial and initial temporal effects of rewetting on C fluxes pose a challenge for process-based modelling and the application of default emission factors for evaluating the effects of rewetting on the peatland C cycle.

CRedit authorship contribution statement

Alexander Pinkwart: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Matthias Peichl:** Writing – review & editing, Methodology, Conceptualization. **Hjalmar Laudon:** Writing – review & editing, Supervision, Funding acquisition. **Järvi Järveoja:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare no use of generative AI in the manuscript preparation process.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.foreco.2026.123669](https://doi.org/10.1016/j.foreco.2026.123669).

Data availability

The data supporting the findings of this study are openly available in the Zenodo digital repository at <https://doi.org/10.5281/zenodo.18957970>.

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