

Plant belowground traits indicate increased plant-mediated methane transport along a peatland permafrost thaw gradient

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Abstract. Permafrost thaw ~~alters in subarctic peatlands alters ecosystem~~ methane (CH₄) fluxes ~~from subarctic peatland ecosystems~~. Collapsing permafrost palsas change hydrology, interstitial oxygen availability, and vegetation composition, and each of these factors contribute to net CH₄ flux by influencing CH₄ production, consumption and transport. ~~CHowever, changes~~ in plant-mediated CH₄ fluxes have mostly been estimated using aboveground characteristics, such as biomass and leaf area, leaving belowground parts (roots and rhizomes) understudied despite their direct contact to depth-dependent CH₄ flux processes. Here, we explored the potential of using root and rhizome traits as proxies for plant-mediated CH₄ cycling along a peatland permafrost thaw gradient in subarctic Sweden. We investigated changes in root and rhizome biomass, surface area (SA), diameter, tissue density (TD), and specific root length (SRL) along the permafrost thaw gradient, and how these traits relate to early-, middle-, peak- and season median CH₄ fluxes. We utilized chamber CH₄ flux and pore water CH₄ concentration and isotopic measurements during the productive season. Shrub SRL, diameter and isotopic data suggested increased plant-mediated carbon substrates available for acetoclastic methanogenesis across the thaw gradient. Root TD, proxy for root porosity, decreased with thaw and had negative correlations with CH₄ fluxes throughout the season. Simultaneously, herbaceous rhizome SA-CH₄ flux correlations were positive and pore water CH₄ concentrations were lowest in the fully thawed stage. These results indicated increasing herbaceous plant-mediated transport of acetoclastically-produced CH₄ with thaw. Our study demonstrates that integrating plant belowground traits with environmental and biogeochemical data can help improve CH₄ flux predictions in thawing landscapes and revealed key mechanistic insights regarding the interplay between substrate availability for methanogenesis and gas transport.

1 Introduction

Northern peatlands are significant net methane (CH₄) emitters primarily due to the predominance of anoxia throughout the peat depth profile (Gorham, 1991; McGuire et al., 2009; Zhuang et al., 2004). Owing to high organic carbon accumulation, high-latitude peatlands store approximately a third of the global carbon stock (Gorham, 1991), with a substantial fraction preserved in and beneath permafrost (Schuur et al., 2008). In the high latitudes, increasing air temperatures drive permafrost thaw, which can expose the previously frozen organic matter to soil decomposers, including methanogens. Together with altered hydrological and thermal conditions, these processes may increase CH₄ emissions and lead to positive climate feedback (Olefeldt et al., 2013; Schuur et al., 2008). Palsa mires with permafrost plateaus (palsas) are especially vulnerable to increasing temperatures and changes in precipitation (Luoto et al., 2004). Palsas are approximately 0.5–10 m high peat hummocks with a frozen core of peat and mineral soil core. They, which form as a result of water-saturated peat freezing in winter and the dry surface peat protecting the frozen peat in summer, raising the peat above the surrounding mire area (Luoto et al., 2004). In northern Fennoscandia, permafrost thaw has formed transitional gradients from frozen palsas and peat plateau to permafrost-free bogs and fens (Luoto et al., 2004; Olvmo et al., 2020; Swindles et al., 2015). Following palsa collapse, soil moisture increases, shifting the system from an ombrotrophic bog-like system to a minerotrophic fen. Vegetation composition shifts from shrub-dominated on (palsas) to graminoid-dominated in (fens), and soil redox and pH change, all of which influencing methanogenic CH₄ production, methanotrophic CH₄ consumption, and CH₄ transport from the soil to the atmosphere, and thus net CH₄ fluxes (Perryman et al., 2020; Turetsky et al., 2014; Varner et al., 2022). Almost all arctic permafrost has been estimated to degrade and result in 120 ± 85 Gt of carbon emissions by 2100 (Lawrence et al., 2008; Schaefer et al., 2014). Together with the inevitable disappearance of palsa mires (Luoto et al., 2004; Olvmo et al., 2020), this highlights the urgent need to investigate the network of CH₄ flux controls in thawing palsa mires.

One of the key biotic CH₄ flux drivers in permafrost peatlands are wetland plants and the traits reflecting their adaptive and resource acquisition strategies. In general, plants contribute to CH₄ fluxes by mediating gas transport, providing carbon substrates for methanogens, and modifying the physicochemical properties of the rhizosphere (Chanton & Dacey, 1991; Gerard & Chanton, 1993; Jeabsson et al., 1999; Laanbroek, 2010; Määttä & Malhotra, 2024; Noyce et al., 2014). As an adaptive strategy to anoxia, many wetland plant species develop aerenchyma which are air spaces within the plant stem, roots and rhizomes that transport oxygen (O₂) from the atmosphere to the roots and the surrounding soil (Armstrong et al., 1991; Končalová, 1990; Vroom et al., 2022). This plant-mediated gas transport mechanism enhances rhizosphere oxygenation and CH₄ consumption, but also simultaneously increases CH₄ transport from anoxic peat to the atmosphere (Laanbroek, 2010; Noyce et al., 2014; Ström et al., 2005). While peatlands store vast quantities of carbon, much of it is too recalcitrant to be directly utilized by methanogens particularly in deep peat (Christensen et al., 1999; Frolking et al., 2010; Hogg, 1993; Ström

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et al., 2005). The release of labile carbon substrates such as acetate and other organic acids by plant roots stimulates CH₄ production and emission (Joabsson & Christensen, 2001; Ström et al., 2003).

Studies using plant functional traits to predict CH₄ fluxes have primarily focused on aboveground features, such as plant green area, even though plant belowground biomass can exceed that aboveground especially in (sub)arctic ecosystems (Iversen et al., 2015; Malhotra & Roulet, 2015). Often, the aboveground traits have been used to estimate belowground characteristics, such as root porosity, based on the plant species or functional type (PFT) (e.g., Bouchard et al., 2007; Greenup et al., 2000; Iversen et al., 2015; Riutta et al., 2007). However, above- and belowground plant traits and the functional connections between them have not been adequately studied in relation to carbon cycling and the use of aboveground traits as proxies for plant-mediated belowground carbon functioning remains unresolved (Iversen et al., 2015; Määttä & Malhotra, 2024).

Many studies have used above- and/or belowground biomass as CH₄ flux predictors but the direction of the relationship varies strongly between studies, species, and PFTs (e.g., Chanton et al., 1997; Greenup et al., 2000; Joabsson & Christensen, 2001; Koelbener et al., 2010; Ström et al., 2005). While above and belowground biomass may reflect plant productivity, quantification of plant-mediated CH₄ fluxes may be better served by a knowledge of belowground traits more directly related to CH₄ production, consumption and transport. For example, root exudation in some instances can explain CH₄ flux variation better than biomass (Ström et al., 2005; Waldo et al., 2019). Because belowground traits, such as rooting depth, change with a deepening active layer (Blume-Werry et al., 2016; Iversen et al., 2015), assessing these trait variations and their effects on CH₄ fluxes along permafrost thaw gradients is essential.

Wetland CH₄ fluxes can be driven by plant-mediated carbon release and CH₄ and O₂ transport (Knox et al., 2021), which can be reflected in root and rhizome traits. Increases in root and rhizome tissue porosity (i.e., lower tissue density and larger diameter; Freschet et al., 2021a; Purnobasuki & Suzuki, 2004; Visser et al., 2000) can enhance plant-mediated gas transport and, depending on species and environmental conditions (e.g., water table level), can lead to increased CH₄ transport and net flux (Bhullar et al., 2013; Henneberg et al., 2012, 2016; van den Berg et al., 2020) or rhizospheric CH₄ oxidation and decreased net CH₄ flux (Dullo et al., 2017; e.g., Fritz et al., 2011; Noyce et al., 2023). CH₄ production can be stimulated by increased labile carbon provision particularly from root exudation (Ström et al., 2003, 2012; Waldo et al., 2019) but also from rhizome and root decomposition (Hackney & De La Cruz, 1980; Scheffer & Aerts, 2000). Specific root length (SRL), the relationship between root length and dry mass, could be a proxy for carbon substrate provision, as high SRL is associated with low tissue density, shorter lifespan, high turnover rates (Bergmann et al., 2020; Eissenstat et al., 2000), and root exudation (Wen et al., 2022). However, studies on the relationships between different root traits, especially SRL and tissue density, in wetlands are rare (Iversen et al., 2015; Pan et al., 2019).

Here, we investigated 1) how root (biomass, surface area, diameter, tissue density, and SRL) and rhizome (biomass, surface area, diameter, and tissue density) traits vary along a peatland permafrost thaw gradient, 2) the correlation of these belowground

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traits with CH₄ fluxes, and 3) whether root and rhizome traits are strong predictors of CH₄ flux during early, middle and peak CH₄ flux during the productive season. We expected that root biomass, surface area and SRL would be highest at the intact and partly thawed permafrost stages due to lower soil moisture and high species diversity (Hough et al., 2022; Iversen et al., 2015; Keuper et al., 2017). We hypothesized that shrub rhizomes would be most abundant in the intact permafrost stage, whereas most herbaceous rhizome biomass would be found in the more thawed permafrost stage (Hough et al., 2022). We hypothesized that root and rhizome tissue density would decrease from intact to fully thawed permafrost due to increased soil moisture. We also expected that SRL would increase CH₄ flux (Saarnio et al., 2004; Ström & Christensen, 2007; Wen et al., 2022), while tissue density would have negative relationships with CH₄ fluxes throughout the productive season. We expected the trait-CH₄ flux relationships to be stronger for herbaceous plants than for shrubs at the middle and peak CH₄ flux periods, because herbaceous plants increase root biomass throughout the growing season in the tundra (Billings et al., 1978; Kummerow & Russell, 1980; Wang et al., 2016) whereas shrub root biomass can remain relatively constant (Wang et al., 2016).

2 Materials and methods

2.1 Study area

The study area is the Stordalen mire in northern Sweden (68° 22' N 19° 03' E; Fig. 1). The mean annual temperature of the area was -0.5 °C and mean annual precipitation sum was 204 mm for period 1985-2023, based on measurements from a nearby meteorological station (Polarforskningssekretariatet & SMHI, 2025a, 2025b). The area contains a permafrost thaw gradient ranging from palsa with intact permafrost to partly and fully thawed permafrost, each of which includes hydrological conditions and vegetation compositions typical for each thaw stage. The permafrost is largely intact in drained palsa with ericaceous shrubs (e.g., *Empetrum nigrum*, *Andromeda polifolia*, *Rubus chamaemorus*), hummock-forming *Eriophorum vaginatum*, mosses (e.g., *Dicranum* sp.) and lichens (Holmes et al., 2022; Hough et al., 2021; Malhotra & Roulet, 2015). In the partly thawed hydrologically perched stage, the vegetation is dominated by *Sphagnum* spp. and feather mosses as well as sedges, such as *Eriophorum vaginatum* and *Carex rotundata*, typical for ombrotrophic bogs (Holmes et al., 2022; Malhotra & Roulet, 2015). The fully thawed stage includes wet minerotrophic fens that have generally higher pH and their dominant vegetation includes *Eriophorum angustifolium*, *Equisetum fluviatile* and *Carex rostrata* (Holmes et al., 2022; Johansson et al., 2006; Malhotra & Roulet, 2015). In general, moisture increases from intact to fully thawed permafrost stages, due to improved connections to the ground water (2007-2017 mean annual water table level ± standard deviation at partly thawed stage: 9.1 ±

4.6 cm below peat surface, fully thawed stage: 2.1 ± 4.4 cm above peat surface) (Crill et al., 2023; Holmes et al., 2022; Malhotra & Roulet, 2015). The peat depth reaches down to 3 m and is underlain by silt (Johansson et al., 2006).

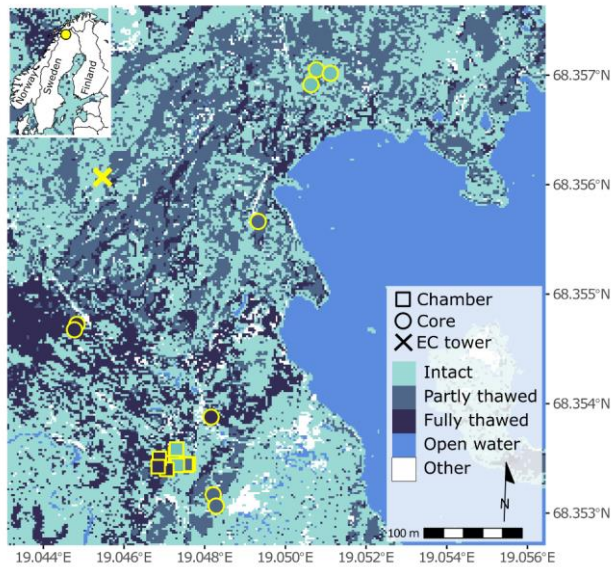


Figure 1: Location of the Stordalen mire and CH₄ flux and peat coring plots within the study area. Based on vegetation classification in 2014, the study area was classified into intact permafrost (tall shrub and hummock, in light blue), partly thawed permafrost (semi-wet and wet, in dark gray), fully thawed permafrost (tall graminoid, in dark blue), open water (bright blue) and other (rock and anthropogenic surfaces, in white) (Palace et al., 2018, 2022; Varner et al., 2022). Rectangles indicate automated chamber CH₄ flux measurement plots, circles indicate peat coring plots, and the cross represents the eddy covariance tower (ICOS: SE-Sto).

2.2 Peat cores

We took peat cores using a push corer (d=12 cm, length=45 cm) to obtain plant material for belowground trait measurements. Despite destructive sampling being restricted, we were able to obtain three cores per thaw stage (n=9 cores in total). In addition, peat coring was not possible next to the CH₄ flux chambers and within the eddy covariance footprint, so we estimated the vegetation composition (vascular plant and moss species) in the chamber collars with vegetation surveys (point intercept method; [Text-Supplementary Methods](#) A1, Table C1) and found representative vegetation patches for each chamber outside of the footprint. In the plot selection, emphasis was put on vascular plant species and secondarily on moss species cover. The

135 peat cores were collected on the 21st of July 2023. The tightly packed samples were put into a cooler with ice packs and stored
frozen for four days. The samples were transported from Sweden to University of Zurich, Switzerland (11 h), and stored in a
freezer in -20 °C until further processing.

2.3 Plant green area measurements

140 To compare the chamber and peat coring plots, and to provide a non-destructive aboveground plant trait comparison to the
belowground traits, we estimated species-specific vascular plant green area (GA; Table 1 and C2). We randomly assigned
three (peat coring plots) to five (chamber plots) subquadrats (16.8 x 16.8 cm) of the vegetation survey grid ([Supplementary
MethodsText A1](#)) for GA measurements using the function sample in R (R Core Team, 2024). We measured green leaf and
stem dimensions (leaf width and length, stem length and diameter) per species within each subquadrat. We measured 10 leaves
per species per subquadrat, with the exception of fully thawed stage chamber plots where we measured all leaves and stems.
For *E. nigrum*, we estimated the total number of leaves by counting all the leaves of three stems roughly representing the
majority of the stems within the subquadrat. We calculated species-specific leaf and stem area (m²) based on geometric
formulae, and GA was estimated based on the average number of green leaves and stems per m² multiplied by green leaf and
stem area per m² (Wilson et al., 2007). Since the leaves of *Rubus chamaemorus* did not fit into a simple geometric formula,
we estimated their green area using photos taken above the survey grid and ImageJ.JS v0.5.8 (Ouyang et al., 2019; Schneider
et al., 2012) (see mean GA per species in Table C2).

150 **Table 1: Vegetation characteristics at CH₄ flux chambers and corresponding peat coring plots at each permafrost thaw stage (intact,
partly and fully thawed). “Core” refers to the plots where peat cores were taken for root and rhizome samples. “Species” includes
the species encountered in the vegetation survey ([Supplementary MethodsText A1](#)), while vascular plant green area (GA)**

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measurements also included species that were not included in the plant cover measurements. “Total” in GA is the mean vascular plant GA across plots per thaw stage. See vegetation coverage at the plot level in Table C1.

Thaw stage	Species	Mean plant cover (%)		Mean GA (m ² m ⁻²)	
		Chamber	Core	Chamber	Core
Intact	<i>Eriophorum vaginatum</i>	66	41		
	<i>Andromeda polifolia</i>	31	27		
	<i>Vaccinium uliginosum</i>	25	24		
	<i>Empetrum nigrum</i>	17	31		
	<i>Rubus chamaemorus</i>	10	15		
	<i>Betula nana</i>	8	20		
	<i>Carex rotundata</i>	4	0		
	<i>Vaccinium vitis-idaea</i>	0	4		
	<i>Ptilium ciliare</i>	48	20		
	<i>Sphagnum balticum</i>	32	0		
	<i>Dicranum</i> sp.	8	27		
	<i>Polytrichum</i> sp.	0	20		
	Herbaceous	45	41	0.01	0.01
	Shrub	83	104	0.04	0.02
				Total: 1.98	Total: 3.61
Partly thawed	<i>C. rotundata</i>	48	48		
	<i>E. vaginatum</i>	0	42		
	<i>V. oxycoccos</i>	32	28		
	<i>A. polifolia</i>	28	24		
	<i>E. angustifolium</i>	0	16		
	<i>Drosera rotundifolia</i>	0	4		
	<i>S. capillifolium</i>	96	89		
	<i>P. ciliare</i>	0	16		
	Herbaceous	48	72	0.004	0.007
	Shrub	31	27	0.001	0.002
				Total: 0.05	Total: 0.09
Fully thawed	<i>E. angustifolium</i>	92	95		
	<i>Equisetum fluviatile</i>	32	44		
	<i>Comarum palustre</i>	4	12		
	<i>S. riparium</i>	26	96		
	Herbaceous	115	128	0.02	0.03
		Shrub	0	0.002	0
				Total: 0.32	Total: 0.8

155 2.4 Environmental variables

In order to compare the abiotic environmental characteristics of the peat coring plots with the chamber plots, we measured [soil](#) [peat](#) temperature (°C), pH, water table level (cm) and active layer depth (cm) at the individual plots (Table 2). Peat temperature

was measured 2-3 times a day (8 AM, 12 PM, 5 PM) at 10 cm depth over a three-day period (July 23rd-25th 2023) using a soil temperature probe (Testo 720, SN 03679207, Testo, Titisee-Neustadt, Germany). Active layer depth was measured with a metal rod.

We measured pH on July 25th 2023. For the intact and partly thawed plots, we took ca. 8.5 g of peat from 0.5 m distance from the chamber collar at ca. 5 cm depth (intact) or 7-10 cm depth (partly thawed). The pH was measured using a pH meter (826 pH mobile, SN 1826001012160, Metrohm, Herisau, Switzerland) and pH electrode (Polyplast, Ref 238380, SN13208, Hamilton, Reno, USA) by mixing the peat sample with CaCl₂ solution (10 ml 0.01 mol/L CaCl₂ per sample). At fully thawed plots, pH was measured directly from open water at ca. 5 cm depth. The electrode was always kept in liquid and when not in measurement solution, it was kept in a protective tube with KCl.

Half-hourly peat temperature data was measured with thermocouples installed at each chamber and acquired with CR10x data logger (Campbell Scientific Inc., UT, USA) (Bäckstrand et al., 2008; McCalley et al., 2014). As continuous soil moisture and water table level data were not available for the productive season in 2023, we used 10-year (2007-2017) water table depth (WTD) means and standard deviations per thaw stage from Crill et al., (2023) for a rough background estimate in soil moisture conditions. To estimate relationships between peat moisture and CH₄ fluxes, we also obtained soil moisture (volumetric water content, %VWC; Table C3) estimates for each chamber using soil moisture sensors (TMS-4 Standard, TOMST s.r.o., Prague, Czech Republic; Wild et al., 2019) at ca. 8 cm depth at ca. 1 m distance from the chambers. The soil moisture values were calibrated to peat using the myClim R package (Man et al., 2023; Wild et al., 2019). To obtain a representative estimate of the central tendency of the dominant peat moisture conditions at each chamber, we used overall chamber medians of daily-aggregated values (non-normal and distributions varied between chambers) from the May-August 2024 and 2025 periods.

Table 2: Peat characteristics at CH₄ flux chambers and peat coring plots per permafrost thaw stage (intact, partly and fully thawed). “Core” refers to the plots where peat cores were taken for root and rhizome samples. See peat characteristics at the plot level in Table C1. ± denotes one standard deviation of the mean. Peat temperature was measured at 10 cm depth. WTD = water table depth (cm from peat surface). VWC = volumetric water content. Note that WTD for chamber plots is the mean annual WTD across the

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2007-2017 period per thaw stage (Crill et al., 2023), and that peat moisture was estimated as overall chamber medians of the 2024-2025 period (see 2.4).

Thaw stage	Mean soil-peat temperature (°C)		Mean pH		WTD (cm)		Mean active layer depth (cm)		Peat moisture (VWC; %)	
	Chamber	Core	Chamber	Core	Chamber	Core	Chamber	Core	Chamber	Core
Intact	8.6 ± 1.1	8.4 ± 1.6	3.01	3.05	-	-	44.3	54	47.4 ± 11.2	±
Partly thawed	9.25 ± 0.6	9.6 ± 2.1	3.3	3.5	-9.1 ± 4.6	-20.9	>85	>85	76.9 ± 31.3	±
Fully thawed	9.05 ± 0.8	9.6 ± 2.1	4.9	5.5	2.1 ± 4.4	>0	>85	>85	100 ± 0	±

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195 2.5 Root and rhizome trait quantification

We cut the frozen peat cores horizontally into minimum 10 cm increments, and then further into four vertical parts (ca. 25%) using a bandsaw. We randomly chose one of the quarters as a subsample for trait measurements. We thawed the subsamples in a refrigerator over 2-3 days and separated the aboveground vascular plants (see species-specific biomass in Table C43). We picked all living roots (light in color and elastic) and rhizomes (stiff, firm bark) from the subsample using tweezers and jeweler’s glasses (2.5x magnification). Due to the very high amount of shrub roots, we took a further subsample (ca. 15 g fresh weight) from which we picked all shrub roots. We cleaned the roots and rhizomes with deionized water and grouped them into herbaceous and shrub PFTs based on a combination of branching patterns, color, and thickness (e.g., shrub roots were generally thinner and had higher branching density than herbaceous roots). The forb *Rubus chamaemorus* was grouped into shrub PFT (e.g., Blume-Werry et al., 2019; Chapin et al., 1988), due to root identification challenges. We did not separate coarse and fine roots but instead focused on the average root system properties. The picked roots were stored in 70% ethanol in a refrigerator (4 °C, max. 4 months).

We put the cleaned roots and rhizomes on a transparent tray filled with deionized water and scanned them with an Epson Perfection V700 Photo scanner (Epson, Japan), and analyzed them for root length, surface area and volume using WinRhizo Pro software (v. 2003b, Regent Instruments Inc., Québec, Canada). We used 1400 dpi for shrub roots with very fine roots (<1 mm), 600 dpi for herbaceous roots, and 100-300 dpi for rhizomes. When rhizome length and diameter were not accurately calculated by WinRhizo, we measured them manually using ImageJ.JS. Then, all roots and herbaceous rhizomes were dried in 70 °C and woody shrub rhizomes in 102 °C for 4 days and weighed at 0.00001 g precision to obtain root and rhizome dry

weight. To obtain a proxy of belowground gas transport potential (i.e., porosity), we calculated root and rhizome tissue density (TD, g cm^{-3}) by dividing their dry weight by fresh volume. For shrub rhizomes, the TD represents all the different rhizome tissues (e.g., bark, wood and pith). While this is not a direct measurement of the gas transport ability of a woody rhizome, low tissue density could indicate increased rhizome aeration (e.g., pith cavities) and possibly gas transport (Covey & Megonigal, 2019; Vroom et al., 2022). Specific root length (SRL, m g^{-1}) was calculated by dividing total root length by its dry weight.

Since peat core depths varied between plots, we standardized root total length (m m^{-2}), biomass (g m^{-2}) and surface area (SA, $\text{m}^2 \text{m}^{-2}$) to 30 cm depth by taking into account core volume and peat bulk density. We also standardized the traits to 10 cm depth for depth-specific analyses. In addition, shrub root and rhizome biomass, length and SA were scaled from the subsample to the increment level and to 30 cm standardized depth. We calculated root and rhizome volumes by summing diameter-class-specific volumes from WinRhizo (Rose, 2017). All traits were calculated per PFT but also summed (biomass, length, and SA) or biomass-weighted (TD, SRL, diameter) to get an across-PFTs trait estimate. We used the rest of the peat core sample (remaining ca. 75%) to determine peat bulk density and gravimetric water content (GWC). We thawed the sample in a refrigerator over 2-3 days, removed the aboveground vascular plants, took a 5 ± 0.2 g subsample, and took its fresh and dry weight to obtain bulk density and GWC.

2.6 CH₄ flux measurements

CH₄ flux data were obtained from automated chambers (see data in Table C54). Briefly, CH₄ flux was measured at each permafrost thaw stage with automated chambers. The details of the chamber measurement system in general are presented in Bäckstrand et al. (2008). In 2012, the chambers were replaced to similar design as in Bubier et al. (2003). In each thaw stage (intact, partly and fully thawed), three transparent automated gas flux chambers (basal area: 0.2 m², height: 15-75 cm) measured CH₄ and CO₂ every three hours with 5-8 min enclosure time and 5 min air flushing before and after closure (Bäckstrand et al. 2008; Holmes et al. 2022). The CH₄ concentrations were measured with a Los Gatos Research Fast Greenhouse Gas Analyzer (Los Gatos Research Inc, Los Gatos, CA, USA) and the timing control and data acquisition was done with Campbell CR10x data logger (Campbell Scientific, Logan, UT, USA), which was located inside a temperature-controlled cabin. The CH₄ flux data were fit using linear regression. The data were quality-checked using regression diagnostics where CH₄ fluxes outside of significance thresholds at 95% and 90% confidence levels were filtered out (Snedecor and Cochran, 1989), as well as manual quality flags that were used to filter out data points affected by known instrumental issues. The CH₄ flux data were fit using linear regression, and data where $R^2 \leq 0.85$ were filtered out.

We aggregated the higher frequency CH₄ flux data to daily scale by taking the daily CH₄ flux median. Median was chosen to estimate the central tendency of CH₄ fluxes due to skewed and non-normal flux data distributions, and to avoid the disproportionate influence of short-lived high CH₄ flux events that may not be related to belowground plant-mediated CH₄ cycling processes that were the main perspective of this study. Then, we subset the daily-aggregated chamber CH₄ flux data

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to contain the dates of the productive season in 2023. We defined the productive season as the period between the first and last passing of daily median net ecosystem CO₂ exchange (NEE) past zero, as this can be considered as the plant active season relevant for plant-mediated CH₄ fluxes (Körner et al., 2023). For NEE, we utilized the half-hourly gap-filled NEE (NEE_VUT: estimated across 40 friction velocity threshold realizations for each year according to FLUXNET data processing protocols; quality flags=3 filtered out) from the ICOS Abisko-Stordalen Palsa Bog (SE-Sto) eddy covariance data processed with FLUXNET standards (Lundin et al., 2025; Pastorello et al., 2020). The resulting productive season used for CH₄ flux data subsetting was 2023-05-19 to 2023-08-30 (Fig. B1). As a background proxy for potential plant carbon substrate provision and plant-mediated gas transport (Knox et al., 2021), we also utilized the half-hourly gap-filled gross primary production (GPP; GPP_NT_VUT: nighttime partitioning at the daily scale and GPP_DT_VUT: daytime partitioning with light response curves at the hourly scale, with variable friction velocity thresholds implemented as an ensemble of 40 friction velocity thresholds by the FLUXNET team; see Lundin et al., 2025 and Pastorello et al., 2020 for details) data from Lundin et al. (2025). However, it is important to note that the EC tower footprint covers only intact and partly thawed stages and does not estimate the NEE and GPP for the fully thawed stage (Lakomiec et al., 2021). To explore the possible diurnal-scale plant-mediated CH₄ transport as a supporting analysis, we also aggregated CH₄ fluxes to the hourly scale using means and medians (Fig. B1).

To explore the variation in the trait-CH₄ flux relationships during the productive season, we calculated CH₄ flux period values (early, middle and peak CH₄ flux) by fitting Gaussian generalized additive models (GAM) with identity link function for daily median CH₄ flux data per chamber with function gam from package mgcv (Wood, 2011, 2017). In the models used for determining CH₄ flux period values, CH₄ flux (response variable) was transformed to approximate normality using inverse hyperbolic sine and date was included as an explanatory variable in a thin plate regression spline. Following an approach similar to TIMESAT (Eklundh & Jönsson, 2015; Jönsson & Eklundh, 2002) and Delwiche et al. (2021), CH₄ flux period values were calculated as follows: 1. peak CH₄ flux: the highest predicted CH₄ flux value during the productive season, 2. early CH₄ flux: the point where the predicted daily CH₄ flux reached 10% of the peak CH₄ flux for the first time, and 3. middle CH₄ flux: the point where the predicted daily CH₄ flux reached 50% of the peak CH₄ flux for the first time. We also calculated the whole season median to represent the whole productive season CH₄ flux estimate per chamber. Since one chamber at intact permafrost thaw stage had GAM R²<0.1, we used a moving 7-day median to estimate the early, middle and peak CH₄ season values. See details of GAM fit in Table C65.

2.7 Porewater CH₄ concentration and isotopic measurements

Data of porewater CH₄ and CO₂ concentrations, δ¹³CH₄ and δ¹³CO₂ were obtained from Wilson et al. (2026). The porewater samples were collected from the field near the automated flux chambers using stainless steel sippers on 25th and 26th of July 2023. The bottom of the sippers is perforated, and a syringe is attached to the top of the sipper via a stopcock. The sipper was inserted in the peat to the desired depth (0-4, 10-14, 20-24, 30-34, 40-44, 50-54, 60-64, 70-74, and 80-84 cm below peat surface) and the syringe was used to carefully draw up 30 mL of porewater. The porewater was then injected into pre-evacuated

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280 sealed glass serum vials. Phosphoric acid (1 mL, 10%) was added to each vial to preserve the samples and ensure that all dissolved inorganic carbon was in the form of dissolved CO₂ in equilibrium with gaseous CO₂. Porewater CO₂ and CH₄ concentrations and isotopes were analyzed simultaneously via headspace analysis, corrected for solubility using Henry's Law, on a Finnigan Mat Delta V Isotope Ratio Mass Spectrometer coupled to a gas chromatograph (Merritt et al., 1995). The analytical uncertainty based on repeated measurements of a standard was <0.15‰ for δ¹³CO₂ and δ¹³CH₄ and <5% for CO₂ and CH₄ concentrations. To obtain a robust estimate of the isotopic fractionation between CO₂ and CH₄, we calculated the isotope fractionation factor (α_C) (e.g., Hodgkins et al., 2014; McCalley et al., 2014) with the following formula:

$$\alpha_C = \frac{\delta^{13}CO_2 + 1000}{\delta^{13}CH_4 + 1000} \quad (1)$$

2.8 Statistical analysis

290 To confirm the similarity of the peat core (n=9) and CH₄ flux plots (n=9), we used principal component analyses (function PCA from package FactoMineR; Lê et al., 2008), PERMANOVA (function adonis2 from package vegan; Oksanen et al., 2025), and Euclidean distances between plots within thaw stages, using normalized plot herbaceous and shrub plant cover and GA, mean [soil-peat](#) temperature and pH (see Fig. B2).

For assessing general differences in daily median CH₄ flux between thaw stages across the productive season, we built linear mixed effects models where CH₄ flux was the response variable and thaw stage (factor) was the explanatory variable, and chamber (n=3 per thaw stage) was the random effect. To account for the normality of residuals and chamber-dependent temporal autocorrelation, we applied inverse hyperbolic sine transformation to CH₄ fluxes, and modeled temporal autocorrelation with autoregressive autocorrelation structure of order 1 (corAR1). We built three different models, where each had either intact, partly or fully thawed permafrost stage as the reference [level, and level and](#) fit the model with restricted maximum likelihood and obtained p-values (α=0.05) from Wald t-test. Linear mixed effects models were built with function lme from package nlme (Pinheiro & Bates, 2000; Pinheiro J, Bates D, R Core Team, 2023).

Due to the small sample size (n=3 per thaw stage), we were unable to test for statistical differences in belowground traits between thaw stages and sampling depths (traits, porewater CH₄ concentration and isotopic data) and relied on descriptive methods. However, to explore the general direction and strength of the relationships between root and rhizome traits and CH₄ fluxes (early, middle, peak, and season median) across the thaw stages, we used linear regressions with centered and scaled trait and CH₄ flux values. Only models which did not violate assumptions of homoscedasticity, linearity and normality of residuals were included in the analyses. In cases with little trait variation within each thaw stage, pseudoreplication was considered too severe for reliable model estimates, and these model results were not reported. We focused on model R², slopes, and model p-values. In cases where linear regressions were unreliable or violated the model assumptions, we explored the relationship strength with Kendall τ correlation coefficients. We acknowledge that the model and correlation estimates can be unstable with small sample size and thus use them as descriptive exploratory tools for estimating the changes in the general

directions of the trait-CH₄ flux relationships across thaw stages during the productive season. All data processing and statistical analyses were conducted in R v4.5.1 (R Core Team, 2025).

3 Results

3.1 Shift from shrub to More herbaceous roots and rhizomes with decreasing tissue density and rhizomes with decreasing tissue density along permafrost thaw

Belowground traits varied between thaw stages, and the biomass-weighted traits followed shifts from shrub- to herbaceous-dominated plant communities (Fig. 2, Table C1). Summed root biomass and surface area (SA) were 22.2x and 17.0x lower, respectively, at the fully thawed than intact stage, but herbaceous root biomass (mean: 238.3 ± 172 g m⁻²) and SA (mean: 19.9 ± 13 m² m⁻²) were highest at partly thawed stage. To note, total shrub root length reached a very high mean of 178.62 km m⁻² and a maximum of 199.7 km m⁻² in the intact stage, substantially higher values than for herbaceous roots (mean: 19.79 km m⁻² and max 33.33 km m⁻² in the partly thawed stage) (Fig. B4). While shrub rhizome biomass and SA decreased from intact to partly thawed stage, herbaceous rhizomes showed an opposite trend (e.g., mean SA 0.13 ± 0 m² m⁻² to 3.41 ± 0.08 m² m⁻², 26-fold increase). Notably, herbaceous root and rhizome tissue density (TD) were 1.5x and 2.4x lower in fully thawed than in intact permafrost, respectively (mean ± standard deviation root 0.004 ± 0.0008 g cm⁻³ to 0.003 ± 0.0002 g cm⁻³; rhizome 0.2 g cm⁻³ ± 0 to 0.08 ± 0.01 g cm⁻³), and these decreases were reflected in the biomass-weighted values (root: 1.5x lower, rhizome: 7.4x lower). While specific root length (SRL) was highest at partly thawed stage (mean shrub 193.6 ± 32 m g⁻¹, 1.4x higher than at intact; mean herbaceous 71.6 ± 35 m g⁻¹, 2.3x and 1.2x higher than at intact and fully thawed, respectively), the biomass-weighted means showed a 2.2-fold decrease from intact to fully thawed stage. Summed root biomass and surface area (SA) were 22.2x and 17x lower, respectively, at the fully thawed than intact stage, but herbaceous root biomass (mean: 238.3 ± 172 g m⁻²) and SA (mean: 19.9 ± 13 m² m⁻²) were highest at partly thawed stage. While shrub rhizome biomass and SA decreased from intact to partly thawed stage, herbaceous rhizomes showed an opposite trend (e.g., mean SA 0.13 ± 0 m² m⁻² to 3.41 ± 0.08 m² m⁻², 26-fold increase).

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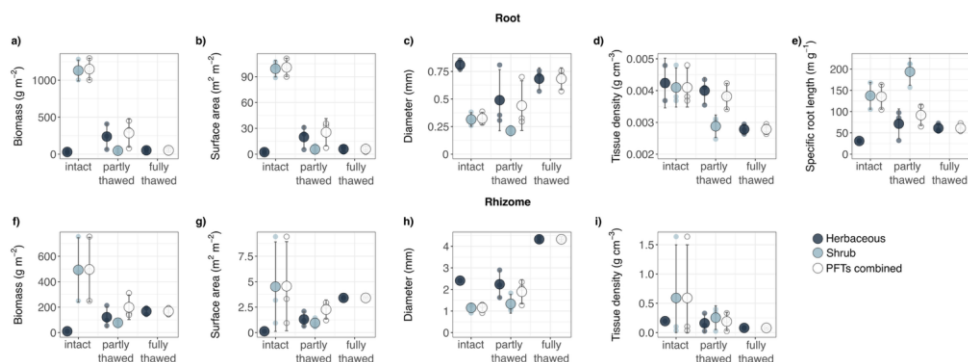


Figure 2: Belowground traits varied between thaw stages. Root traits (a-e) are shown in the top row and rhizome traits (f-i) in the bottom row. Large points represent group means, small points plot-scale measurements, and error bars ± 1 standard deviation of the mean. The colors represent plant functional types (PFT; dark grey: herbaceous, light grey: shrub, white: PFTs combined). Trait values for combined PFTs were summed herbaceous and shrub values (a, b, f, and g) or biomass-weighted means between herbaceous and shrub PFTs (c-e, h and i).

Most of the root biomass was found in the top 10 cm for shrub (coefficient of variation CV and mean for intact: 69%, 766.0 $\pm$ 155 g m⁻²; partly thawed: 67%, 65.1 $\pm$ 28 g m⁻²) and herbaceous PFTs (CV and mean intact: 56%, 17.5 $\pm$ 9 g m⁻², partly thawed: 45%, 86.4 $\pm$ 89 g m⁻², fully thawed: 73%, 27.7 $\pm$ 20 g m⁻²) (Fig. B3). Shrub roots reached the maximum total length of 167.3 km m⁻² at top 10 cm at the intact stage (Fig. B4). SRL and root TD varied less with depth across thaw stages (max CV SRL: 51%, TD: 31%; partly thawed herbaceous). All herbaceous rhizomes were present in the top 10 cm (mean biomass intact: 11.5 $\pm$ 0 g m⁻², partly thawed: 101.9 $\pm$ 109 g m⁻², fully thawed: 107.8 $\pm$ 12 g m⁻², Fig. B5). Most of the shrub rhizomes were located in the top 10 cm (CV and mean biomass intact: 78.5%, 392.4 $\pm$ 227 g m⁻²; partly thawed: 66.7%, 93.9 $\pm$ 15 g m⁻²), but they were also found in 10-20 cm depth (mean intact: 109.4 $\pm$ 154 g m⁻², partly thawed: 28.9 $\pm$ 0 g m⁻²).

3.2 Root tissue density, specific root length and diameter correlated best with CH₄ fluxes

The relationships between root traits and CH₄ fluxes (CH₄ flux difference between intact, partly and fully thawed p<0.015, fully and partly thawed p>0.05, [Supplementary Methods Text A2](#)) differed between PFTs but with little temporal variation. Increasing root TD was associated with decreasing CH₄ flux for herbaceous (min standardized regression beta coefficient, β = -0.86 R²=0.73 at peak CH₄, max β = -0.91 R²=0.82 at middle CH₄ season median) and shrub PFTs (min β = -0.56 R²=0.31 at middle CH₄ season median, max β = -0.75 R²=0.56 at middle CH₄ season median) (Fig. 3, B6). Shrub root diameter had negative (min β = -0.74 R²=0.55 at early CH₄ season median, max β = -0.87 R²=0.76 at middle CH₄ season median) and SRL positive (min β = -0.67 R²=0.45 at early peak CH₄, max β = -0.74 R²=0.54 at middle and peak CH₄ season median) associations

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with CH₄ fluxes. In general, the direction and strength of the relationships between root traits and CH₄ fluxes did not vary strongly across CH₄ flux season values (Fig. 35, B65).

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PFTs combined, all root traits except diameter showed negative trends, where the strongest relationships were for root TD (min $\beta = -0.82$ $R^2 = 0.67$ 0.68 at early and; peak and season median-CH₄, max $\beta = -0.85$ $R^2 = 0.73$ at middle CH₄) (Fig. 3, B7). In addition, summed root biomass and SA showed relatively strong negative relationships, with biomass showing slightly stronger negative relationships than SA (biomass: min Kendall's $\tau \beta = -0.68$ $R^2 = 0.46$ at early CH₄ season median, max $\tau \beta = -0.81$ $R^2 = 0.66$ at early middle CH₄; SA: min $\tau \beta = -0.63$ $R^2 = 0.4$ at early CH₄ season median, max $\tau \beta = -0.8$ $R^2 = 0.64$ at early peak CH₄) (Fig. B67).

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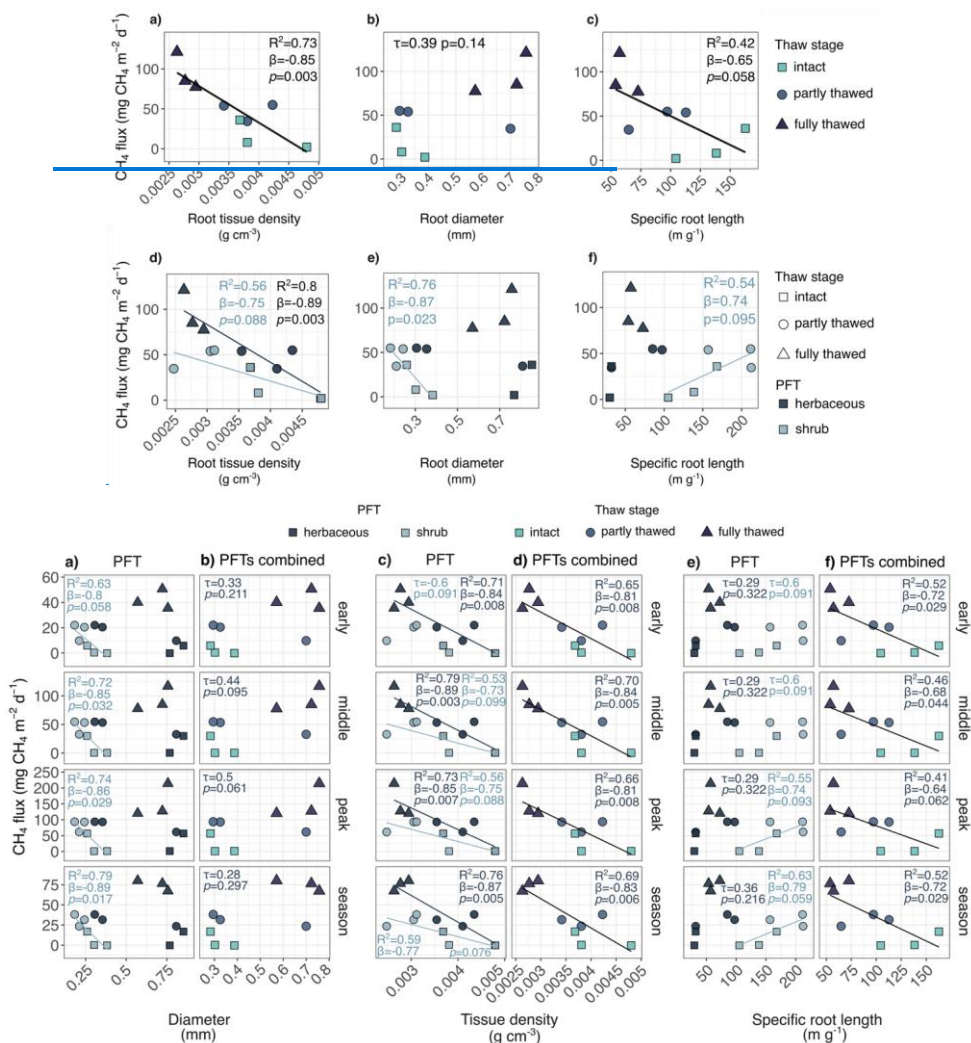


Figure 33: Root tissue density, diameter, and specific length showed strongest relationships with mid-season CH₄ fluxes. **a-be)** Relationships between root diameter and CH₄ fluxes (early, middle, peak and season) per plant functional type (PFT; a) and across PFTs (biomass-weighted means; b). **c-d)** Relationships between root tissue density and CH₄ fluxes per PFT (c) and across PFTs

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(biomass-weighted means; d). e-f) Relationships between specific root length and CH₄ fluxes per PFT (e) and across PFTs (biomass-weighted means; f). In a, c and e, dark gray: herbaceous plants, light gray: shrubs, biomass-weighted means and CH₄ fluxes at middle flux period (In b, d and f, light blue rectangle: intact, light grey circle: partly thawed, dark purple triangle: fully thawed stage). d-f) PFT-specific (dark gray: herbaceous, light gray: shrub) trait-CH₄ flux relationships at mid-season CH₄ flux. In all plots (a-f), lines represent linear regression for visualization, while R² and standardized effect size/slope (β) are based on linear regressions with centered and scaled trait and CH₄ flux values (lines, R² and β are only shown when R²>0.2, model p<0.1, and the linear regression model assumptions were met). Kendall's τ is shown for relationships where linear regression model assumptions were not met and, τ≥0.24 and p<0.1 (note that due to the low sample size, p-values should be interpreted with caution). The shown trait-CH₄ flux relationships were selected based on R² or τ. See relationships between root biomass, surface area and all CH₄ fluxes season values and all root traits in Fig. B66 and B7.

Herbaceous and shrub rhizome traits showed contrasting relationships with CH₄ fluxes (Fig. 4, B78). Herbaceous rhizome biomass and SA showed positive relationships with CH₄ fluxes, with stronger trends for SA (SA: min β =0.9 R²=0.8 at peak CH₄, max β at =0.97 R²=0.94 0.95 at early-CH₄ and season median; biomass: min β=0.52 R²=0.52 at early-CH₄ and season median, max β=0.75 R²=0.57 at middle and peak CH₄). Increases in herbaceous rhizome diameter were also associated with slightly higher CH₄ fluxes (min τ =0.33 p=0.348 at early to peak CH₄, max τ =0.6 p=0.091 at CH₄ season median). In contrast, shrubs had negative trends between rhizome biomass and CH₄ fluxes (min τ =-0.07 p=0.851 at early, middle and season median CH₄ season median, max τ =-0.6 p=0.091 at peak early CH₄; Fig. B7). While summed rhizome SA did not show clear trends (Fig. 4), higher summed rhizome biomass was associated with lower CH₄ fluxes (min nonsignificant β =-0.63 R²=0.4 at early early-CH₄, max β =-0.8 R²=0.63 at peak CH₄; Fig. B7-peak), while the relationship between rhizome diameter and CH₄ flux was positive (min τ =-0.43 p=0.138 at early and middle CH₄ peak and season median, max τ =0.64 p=0.026 at early-peak and season median CH₄) (Fig. 4B9).

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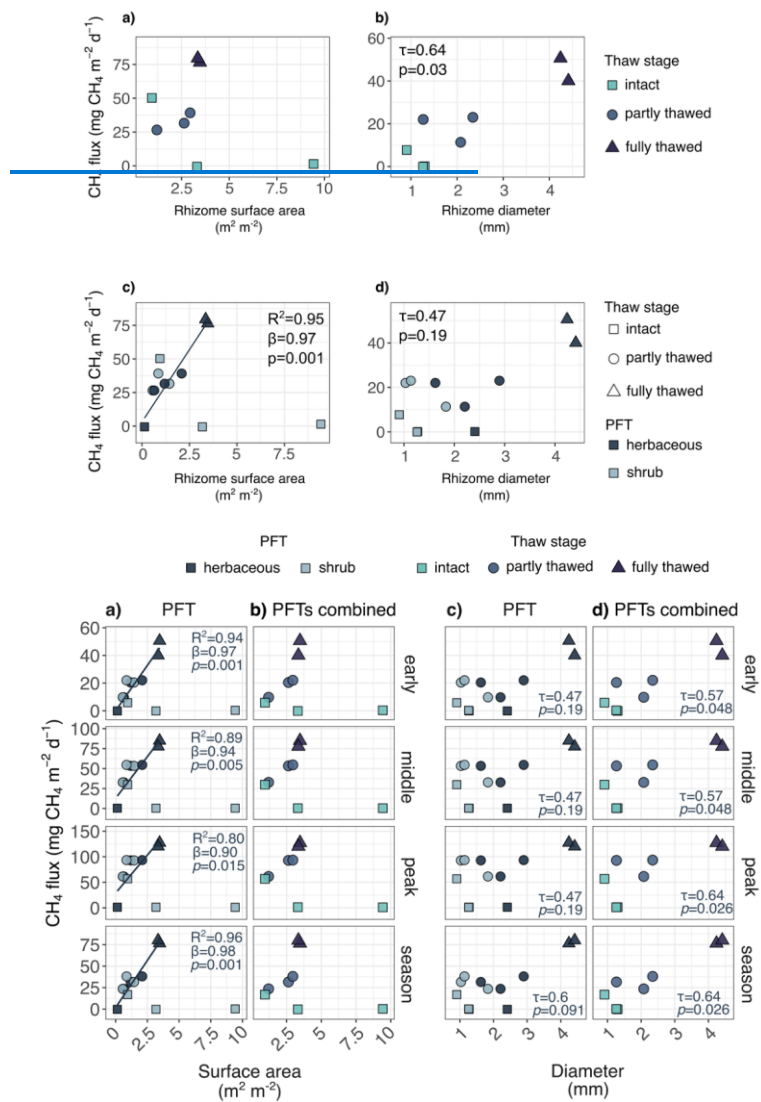
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395 **Figure 44:** Relationships between rhizome traits and CH₄ fluxes were strongest for surface area and diameter. **Columns a-b)**
 Relationships between summed rhizome surface area and CH₄ season median fluxes (early, middle, peak and season; rows) per plant
 functional type (PFT; a) and across PFTs (summed; b). Columns c-d) Relationships between rhizome diameter and CH₄ fluxes per
 PFT (c) and across PFTs (biomass-weighted means; d). In a and c, dark gray color represents herbaceous plants while light gray
 represents shrubs. In b and d, (a) and biomass-weighted rhizome diameter means and early-season CH₄ (b) (light blue rectangles
 400 represent the: intact permafrost, dark blue circles represent the: partly thawed stage, and dark purple triangles represent the: fully
 thawed stage). c-d) Relationships between rhizome surface area and CH₄ season median (c) and rhizome diameter and early-season
 CH₄ (b) per PFT (dark gray: herbaceous, light gray: shrub). Lines represent linear regressions for visualization, while R² and
 standardized effect size/slope (β) are based on linear regressions with centered and scaled trait and CH₄ flux values (lines, R² and
 β are only shown when R²>0.2, model p<0.1, and the linear regression model assumptions were met). Kendall's τ is shown for
 405 relationships where linear regression model assumptions were not met and, τ>0.24 and p<0.1. The shown trait-CH₄ flux relationships
 were selected based on R² or τ. See relationships between all rhizome biomass, tissue density and CH₄ fluxes values and all rhizome
 traits in Fig. B78 and B9.

In comparison with belowground trait relationships, CH₄ fluxes were weakly and positively correlated with plant green area
 (GA) and soil-peat temperature (Fig. B840). GA, which also did not show clear trends with permafrost thaw (Fig. B944),
 showed no clear relationships with CH₄ fluxes (max τ = -0.62 p=0.05 for shrub at peak CH₄; Fig. B8 season median). Soil-Peat
 410 temperature did not show clear relationships with CH₄ fluxes (except max τ = -0.44 p=0.095 at peak-middle CH₄; Fig. B8).
 However, increases in peat moisture were generally associated with higher CH₄ fluxes (τ=0.73 at early, middle and season
 median CH₄; Fig. B8), with the highest CH₄ fluxes occurring in the wettest plots in the fully thawed stage (median
 VWC=100%), and lowest CH₄ fluxes in the drier intact stage (median VWC=43.4%).

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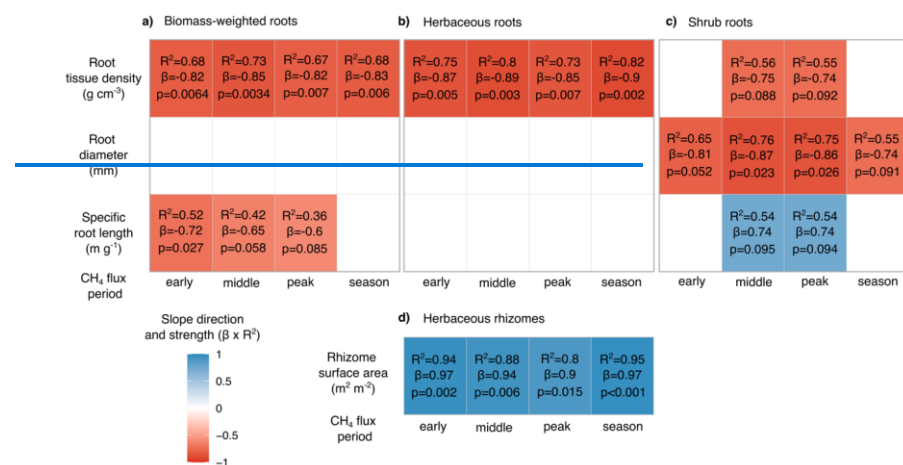


Figure 5: The strength of the relationship between belowground traits and CH₄ fluxes varied only slightly during the productive season. The strength and direction of the relationship is described as the combination of linear regression slope (β ; red = negative, blue = positive) and model R^2 (darker colors indicate higher R^2 and vice versa). Model p -values are shown for reference. White cells without labels indicate models where $p>0.1$, $R^2<0.2$ or model assumptions were violated. a-c) Strength and direction of the linear regression between CH₄ fluxes and biomass-weighted (a), herbaceous (b) and shrub root traits (c) and herbaceous rhizome surface area (d). Note that only CH₄ fluxes were sampled temporally but root and rhizome traits were sampled once during the productive season. See relationships between all root and rhizome traits and CH₄ flux values in Fig. B6-B9.

4 Discussion

Permafrost thaw in subarctic peatlands can lead to substantial alterations in peatland hydrology, vegetation composition and carbon cycling, and higher CH₄ emissions with higher water table level and more anoxic conditions belowground (Johnston et al., 2014; Knoblauch et al., 2018; Turetsky et al., 2014; Varner et al., 2022). These trends were visible in the Stordalen Mire where CH₄ fluxes increased significantly from intact to fully thawed permafrost stage with maximum CH₄ fluxes in August (Text Supplementary Methods A2 and Fig. BFig-B102), and porewater CH₄ concentrations increased with depth and CH₄ production slightly shifted from hydrogenotrophic to acetoclastic methanogenesis (Fig. B113), as has been observed previously at Stordalen (Hodgkins et al., 2014; Holmes et al., 2022; McCalley et al., 2014; Perryman et al., 2020; Varner et al., 2022). Shifts from hydrogenotrophic to acetoclastic methanogenesis can indicate increased root exudate-driven CH₄ production (see 4.2) (Saarnio et al., 2004; Ström et al., 2003).

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The increased CH₄ fluxes with permafrost thaw in Stordalen are driven by a complex network consisting of drivers such as higher water table level and increased anoxia (Holmes et al., 2022; Malhotra & Roulet, 2015), higher peat temperatures at the end of growing season (Mollenkopf et al., 2026), increased labile carbon availability (Hodgkins et al., 2014; Holmes et al., 2022; Hough et al., 2022), shifts in microbial communities from hydrogenotrophic to acetoclastic methanogens (McCalley et al., 2014), and increasing dominance and productivity of graminoid vegetation (Christensen et al., 2004; Johansson et al., 2006; Malhotra & Roulet, 2015; Öquist & Svensson, 2002; Varner et al., 2022). For the first time in Stordalen and, to our knowledge, in other thawing permafrost peatlands, we studied explored the permafrost thaw driven effect of belowground plant traits on CH₄ fluxes variation with a plant trait-based approach with a focus on belowground traits. In general, root and rhizome traits reflected plant community transitions and were consistent with an increase in plant-mediated transport of acetoclastically-produced CH₄.

4.1 Root and rhizome traits reflect plant community shifts along permafrost thaw gradient

The vegetation composition in Stordalen follows the changing hydrology and soil nutrient availability. The vegetation shifts from shrub-dominated (intact stage; e.g., *R. chamaemorus*, *B. nana*, and *E. nigrum*) palsas to increasingly more graminoid- and *Sphagnum*-dominated semi-wet bogs (partly thawed; e.g., *V. oxycoccus*, *C. rotundata*, and *S. capillifolium*) and wet fens (fully thawed; *E. angustifolium*, *E. fluviatile*, and *S. riparium*; Table C1 and C2) (Hough et al., 2022; Johansson et al., 2006; Malhotra & Roulet, 2015; Malmer et al., 2005; Varner et al., 2022). Following these vegetation transitions, plant traits reflect plant adaptation to the changing environmental conditions (Díaz et al., 2016; Dong et al., 2020; Moor et al., 2017; Pan et al., 2019; Reich et al., 1997). While studying plant trait variation and its influence on ecosystem functioning often requires species-specificity to capture changes in diversity (Freschet et al., 2017; Kichenin et al., 2013; Vahsen et al., 2023; Violle et al., 2014) and separation into fine and coarse root fractions (Freschet et al., 2021b; McCormack et al., 2015), CH₄ flux models often utilize PFTs which have been found to adequately represent the collective trait effects on CH₄ fluxes in peatlands (Gray et al., 2013; Laine et al., 2022). Thus, we here focused on root and rhizome traits at the PFT (herbaceous and shrub) level. This approach provides empirical constraints on plant-mediated carbon substrate provision and CH₄ transport that can inform parameterization and sensitivity analyses in process-based wetland CH₄ models, such as LPJ-GUESS (Smith et al., 2001, 2014), and HIMMELI (Raivonen et al., 2017).

Following vegetation community shifts, most belowground shrub biomass and total length were found in the intact stage while herbaceous biomass increased from intact to fully thawed stage. The shrub root biomass values were lower than previous estimates for *R. chamaemorus*, *E. nigrum* and *A. polifolia* (total >2000 g m⁻²) in Stordalen (Wallén, 1986), but are much higher than recent belowground biomass estimates (~280 g m⁻²; Hough et al., 2022). In addition, Hough et al. (2022) reported higher total root biomass at the fully thawed (~218 g m⁻²) than partly thawed stage (~146 g m⁻²), whereas this study showed the opposite (Fig. 2). These differences could arise from different root biomass standardization and sampling methods, a problem highlighted in root ecology (Freschet et al., 2021a): Wallén (1986) calculated fine root biomass based on ¹⁴C activity which

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can lead to overestimations (Wallén, 1986), while Hough et al. (2022) sampled a larger area (625 cm²) than in our study (~79 cm²), leading to differences particularly at the fully thawed stage, where graminoids root more vertically than laterally. In addition, our root samples may have consisted of a different mix of species than in Hough et al. (2022), which together with the low sample size, may have influenced these results. Nonetheless, root biomass decreased by depth, as is common particularly for shrubs (Iversen et al., 2015; Wallén, 1986). As we observed *R. chamaemorus* roots up to 30 cm depth, similar to Wallén (1986) and Keuper et al. (2017) in Stordalen and by Metsävaio (1931) in Finnish peatlands, and as *E. angustifolium* and *E. fluviatile* roots have been found at 40 cm depth (Iversen et al., 2015; Metsävaio, 1931; Shaver & Billings, 1975), the maximum rooting may occur deeper than our sampling depth (ca. 30 cm). In general, these findings, and particularly the remarkably high total shrub root length values, showed that permafrost-affected peat soils are rich in plant roots and likely contribute to the carbon cycling of these ecosystems (Bardgett et al., 2014; Iversen et al., 2015).

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Variation in tissue density (TD) and specific root length (SRL) (Fig. 2) with thaw suggest changes in plant gas transport and resource acquisition. Increasing soil moisture with thaw (via higher water table level; Table 2 and Fig. B8) and subsequent aerenchyma formation (e.g., Jackson & Armstrong, 1999) may have decreased TD. The increase in herbaceous rhizome SA may reflect greater aerenchyma proportion, confirming rhizome SA as a proxy for plant gas transport capacity. SRL was highest and root diameter lowest at the partly thawed stage, which could possibly reflect increased resource acquisition particularly for shrubs (Bergmann et al., 2020), but further research with larger sample sizes is needed to investigate the potential changes in shrub resource acquisition with high SRL and low root TD (Bergmann et al., 2020). As the peat C/N ratio is highest in the partly thawed stage (Hodgkins et al., 2014), the high SRL may reflect low N availability, shifts in species and species-specific resource acquisition (Hewitt et al., 2019; Keuper et al., 2017). However, as fine root SRL is more meaningful for resource acquisition (Bergmann et al., 2020; McCormack et al., 2015), our results based on the whole root system provide only a rough estimate. Nonetheless, 99% of total shrub root length was <2 mm in diameter (vs. 31%, 75%, and 63% in intact to fully thawed stages, respectively, for herbaceous), and thus within the traditional fine root definition (McCormack et al., 2015).

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4.2 Belowground traits reflect increasing plant-mediated CH₄ transport

The increasing peat moisture and associated changes in belowground plant traits contributed to the increasing CH₄ fluxes along the permafrost thaw gradient. Given our exploratory results (see 3.2 and Fig. B8) and earlier studies conducted at Stordalen (Holmes et al., 2022; Malhotra and Roulet, 2015), the increasing peat moisture was likely one of the primary drivers of the increasing CH₄ fluxes along the thaw gradient. While the main CH₄ flux drivers in Stordalen are likely related to soil moisture and water table height (Holmes et al., 2022; Öquist & Svensson, 2002), however, due to the low sample size we were unable to separate the effects of plant traits and peat moisture in multivariate models, and larger sample sizes are recommended to analyze the interactions between peat moisture and plant belowground traits in future studies. Nonetheless, the univariate relationships between plant belowground traits and CH₄ fluxes indicated 1) maintained carbon substrate provision and 2)

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500 increasing plant-mediated CH₄ transport across the permafrost thaw gradient. In Stordalen, permafrost thaw has led to increasing plant-derived labile carbon availability and acetoclastic methanogenesis (Hodgkins et al., 2014; Holmes et al., 2022; McCalley et al., 2014; Ström & Christensen, 2007), but plant-mediated CH₄ transport has so far been mostly assumed based on literature and plant aboveground characteristics and activity, such as number of shoots and gross photosynthetic rates (Öquist & Svensson, 2002).

505 Shrub roots suggested increasing carbon substrate provision. The higher CH₄ fluxes with increasing shrub SRL (and smaller diameter; Bergmann et al., 2020) may be related to increased root exudation (Guyonnet et al., 2018; Wen et al., 2022). The negative root TD-CH₄ flux relationships support this, as higher root TD may be associated with lower root exudation (Wen et al., 2022). In contrast, herbaceous SRL was weakly associated with CH₄ fluxes, possibly due to decoupling of root exudation and SRL in some Cyperaceae species in nutrient-limited environments (Wen et al., 2022), and the SRL also including coarse roots (Picon-Cochard et al., 2012). However, based on the ¹³C-depleted δ¹³CH₄ and high α_C, hydrogenotrophic methanogenesis
510 ~~driven by methanogens such as *Methanobacterium* and *Candidatus Methanoflorens stordalenmirensis*~~, may have dominated in the topmost peat, and most of the dissolved, less bioavailable organic carbon possibly originated from *Sphagnum* in the partly thawed stage (Hodgkins et al., 2014; McCalley et al., 2014; Mondav et al., 2014; Wilson et al., 2022). Nonetheless, the lower α_C, more enriched δ¹³CH₄, and higher CH₄ concentrations below the root sampling depth (30-44 cm) indicated
515 acetoclastic methanogenesis (Fig. B113) (e.g., by *Methanosarcina*; McCalley et al., 2014), possibly fueled by root exudates (Saarnio et al., 2004; Ström et al., 2003; Ström & Christensen, 2007). Indeed, based on photosynthetic rates, the partly thawed stage has been estimated to have more labile carbon for methanogenesis (Öquist & Svensson, 2002), and *E. angustifolium* and *E. vaginatum* have high potential root exudation rates in Stordalen (Ström & Christensen, 2007) and graminoid root exudation
520 rates can exceed that of shrubs in the partly and fully thawed stages (Mollenkopf et al., 2026). Based on these previous studies, it is possible that the SRL based on the whole heterogeneous root system did not represent the potential root exudation accurately for herbaceous plants. Thus, roots (including herbaceous) may have exuded labile carbon, but with shrubs having a lesser effect on the net CH₄ flux.

525 Herbaceous plant coverage increased with thaw, which was reflected in traits indicating plant-mediated CH₄ transport (Fig. 2, Table C1). Higher herbaceous rhizome SA was positively associated with greater CH₄ fluxes, which, together with the positive diameter-CH₄ flux trends, could indicate enhanced CH₄ transport via larger and more porous rhizomes (Määttä & Malhotra, 2024). Rhizome-mediated CH₄ transport could be particularly relevant for plants with pressurized gas transport, such as *Equisetum* spp., where pressure gradients between the atmosphere, leaves, and rhizomes can drive CH₄ emission via old leaves
530 and broken stems (Vroom et al., 2022). As shrub rhizomes were not associated with CH₄ fluxes (Fig. 4, B8), they may not drive plant-mediated CH₄ cycling in Stordalen, though standardized measurements of, e.g., rhizome length and biomass are needed to confirm this (e.g., Freschet et al., 2021a).

Plant-mediated CH₄ transport may have been pronounced in the fully thawed stage with high [peat moisture](#), herbaceous plant coverage, and low porewater CH₄ concentrations (Table C1 and Fig. [B4-B8, B11](#)), indicating plant CH₄ uptake. As low root and rhizome TD indicates higher porosity (Ye & Ryser, 2022), the negative relationships between root TD and CH₄ flux suggest increased plant-mediated CH₄ transport [in response to increasing peat moisture](#). The isotopic evidence (heavier δ¹³CH₄ and lower α_c) may further suggest plant-mediated transport of acetoclastically-produced CH₄ at the fully thawed stage (Chanton, 2005). This supports previous findings of higher herbaceous shoot numbers increasing CH₄ flux in the fully thawed stage (Öquist & Svensson, 2002). [However, a recent study conducted in the same productive season found that 30% of the CH₄ flux in the fully thawed stage consisted of graminoid plant-mediated CH₄ transport and the rest of CH₄ production stimulated by graminoid root exudation, while in the partly thawed stage plant-mediated CH₄ transport dominated the CH₄ flux \(80%\) \(Mollenkopf et al., 2026\). Nonetheless, both this and the study by Mollenkopf et al. \(2026\) together suggest increased herbaceous plant-mediated CH₄ transport and carbon substrate provision in the fully thawed stage.](#) In Stordalen, most of the plant-mediated CH₄ transport likely occurs via diffusion, typical for *Carex* spp., *E. angustifolium*, and *E. vaginatum* (e.g., Ge et al., 2025; Noyce et al., 2014; Bhullar et al., 2013). CH₄ diffusion may be more efficient through *E. angustifolium* with low root branching in the fully thawed than at partly thawed stage with more densely rooted *Carex* species (Schimel 1995; Shaver & Billings, 1975; Table C1). However, pressurized CH₄ transport via *Equisetum fluviatile* (in fully thawed stage) could be negligible and requires further investigation as we did not separate the belowground material into species (Hyvönen et al., 1998; Kankaala & Bergström, 2004). As graminoid (e.g., *E. angustifolium*) roots have low bioavailability in the fully thawed stage (Hough et al., 2022), and root porosity and decomposability may be decoupled (Pan et al., 2019; Ye & Ryser, 2022), the low root and rhizome TD were unlikely to lead to increased decomposition and carbon substrate provision.

[Simultaneously to plant-mediated CH₄ transport, herbaceous roots may have enhanced rhizospheric CH₄ oxidation. Previous studies at Stordalen have reported shifts in methanotroph communities with thaw as well as an increase in CH₄ consumption, which may result from greater plant-mediated rhizospheric oxidation \(i.e., more O₂ transport with lower root TD\) and acetoclastic methanogenesis \(Perryman et al., 2020; Singleton et al., 2018\). Simultaneously to plant-mediated CH₄ transport, herbaceous roots may have enhanced rhizospheric CH₄ oxidation. Methanotrophic CH₄ consumption increases with thaw in Stordalen with changes in methanotroph communities from e.g., *Methylocystaceae* in the partly thawed stage to *Methylococcaceae* in the fully thawed stage, which may result from greater plant-mediated rhizospheric oxidation and acetoclastic methanogenesis \(Perryman et al., 2020; Singleton et al., 2018\).](#) In addition, *Sphagnum* spp. can host methanotrophic CH₄-consuming bacteria (e.g., Larmola et al., 2010; Putkinen et al., 2014; [Raghoebarsing et al., 2005](#)), [which may have increased CH₄ consumption in the more O₂-rich intact and partly thawed stages dominated by *S. balticum* and *S. capillifolium*, with intact stage chambers possibly having higher CH₄ consumption rates than peat cores with no *S. balticum* \(Table 1\).](#) However, the average δ¹³CH₄ emitted from the partly thawed chamber plots was -79.6 ± 0.9 ‰ in 2011, similar to or ¹³C-depleted relative to the porewater CH₄ at the same sites, indicating little CH₄ oxidation (McCalvey et al., 2014). Thus, the heavier δ¹³CH₄ in the fully and partly thawed stages could also indicate increased CH₄ oxidation close to O₂-rich air at the

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topmost peat or in the oxidized rhizosphere at ca. 20–44 cm depth (Perryman et al., 2020; Singleton et al., 2018). In addition, during CH₄ oxidation, methanotrophs preferentially consume lighter, $\delta^{12}\text{CH}_4$, enriching the remaining CH₄ pool in $\delta^{13}\text{C}$ while producing isotopically light CO₂ (Whiticar, 1999). However, isotopically light CO₂ could also indicate less methanogenesis instead of increased methanotrophy, and rhizospheric $\delta^{13}\text{CH}_4$ enrichment can also result from faster plant $^{12}\text{CH}_4$ uptake and increased plant-mediated CH₄ transport (Chanton, 2005). However, rhizospheric $\delta^{13}\text{CH}_4$ enrichment can also result from faster plant $\delta^{12}\text{CH}_4$ uptake and increased plant-mediated CH₄ transport (Chanton, 2005). Thus, based on the lower α_c (i.e., maintained acetoclastic methanogenesis) at 20–44 cm depth, and the strongly negative relationships between root TD and CH₄ fluxes (i.e., decreasing amount of aerenchyma is related with lower CH₄ fluxes and vice versa), it seems that the CH₄-oxidizing effect of herbaceous plants particularly in the fully thawed stage is overshadowed by increased carbon provision for methanogenesis and enhanced plant-mediated CH₄ transport. Thus, based on the lower α_c (i.e., maintained acetoclastic methanogenesis) at 20–44 cm depth, and the strongly negative relationships between root TD and CH₄ fluxes it seems that the CH₄-oxidizing effect of herbaceous plants particularly in the fully thawed stage is overcome by provision of carbon for methanogenesis and, shown here with belowground traits for the first time, enhanced plant-mediated CH₄ transport.

4.3 Belowground trait relationships with CH₄ fluxes did not vary within the productive season

The relationships between the static belowground traits and CH₄ fluxes (early, middle, peak, and season median) did not vary strongly within the productive season—early, middle, peak, and season median CH₄ fluxes differed only slightly in strength. This may result from the lack of temporal root and rhizome sampling within the productive season. However, as an exploratory analysis, our results may indicate higher herbaceous plant-mediated CH₄ transport at the middle CH₄ flux period (Fig. 35). In contrast to our hypotheses, shrub root traits were more strongly associated related (i.e., higher linear regression β and R^2) with middle and peak and season median CH₄ fluxes whereas herbaceous root (TD) and rhizome (SA) traits were strongly associated related with CH₄ fluxes throughout the season. This could result from the lack of temporal sampling, but also from low temporal variation in *E. angustifolium* and *E. vaginatum* root porosities not responding strongly to changes in waterlogging (Smirnov & Crawford, 1983), possibly keeping plant-mediated CH₄ transport constant. In addition, coarse root diameter (diameter is used for determining root TD; see 2.5) does not vary strongly temporally (Picon-Cochard et al., 2012), possibly contributing to the lack of temporal trends between root diameter and CH₄ fluxes. Thus, the root TD-CH₄ flux relationships may have reflected higher CH₄-transporting herbaceous root biomass at the middle and peak CH₄ flux period (July–September; Shaver & Billings, 1977) instead of temporal TD and diameter variation. Indeed, diffusive plant-mediated CH₄ transport via *Carex* spp. could be high during the mid- and peak-growing season, as for example *Carex rostrata* (present at the partly and fully thawed stages but not captured by our aboveground measurements; see Table C1 and e.g., Hough et al., 2022) has been found to transport most CH₄ at high summer and early autumn (Ge et al., 2025; Noyce et al., 2014). Furthermore, a study conducted in Stordalen during the same productive season found that plant-mediated CH₄ transport and carbon substrate provision via graminoids was highest in August and September, further confirming these results (Mollenkopf et al., 2026). In addition, gross primary production (GPP), a proxy for plant-mediated gas transport (Knox et al., 2021), peaked in July and

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605 August (max monthly medians: 3.87 and 2.79 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively; Fig. B1). Concurrently, and CH_4 fluxes at the partly and fully thawed stages were slightly higher during nighttime (Fig. B1). Both of these GPP and CH_4 flux trends which could further indicate seasonally (via higher herbaceous plant biomass) and diurnally (via stomatal opening and closure) varying plant-mediated CH_4 transport. However, (but as GPP and CH_4 flux peaks did not coincide in the same hourly time periods, further research into diel CH_4 fluxes and plant-mediated CH_4 transport is needed; (Fig. B1) (Knox et al., 2021). As *Carex*, *Eriophorum* and *Equisetum* rhizomes are perennial (Husby, 2013; Shaver, 1976), the pre-existing rhizomes may have contributed to CH_4 transport particularly in the beginning of the productive season with active root growth (esp. *E. angustifolium*; Shaver & Billings, 1975), resulting in strong rhizome- CH_4 flux relationships (Fig. 4, B75).

610 Our exploratory analyses suggested stronger shrub carbon substrate provision (SRL and diameter) at middle-and-peak CH_4 flux period and across the seasons (season median; Fig. 35). While uncertain due to the static trait values, these results could be supported by the greater gross primary production (GPP) at the intact and partly thawed stages (Łakomiec et al., 2021) in July and August ((max monthly medians: 3.87 and 2.79 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively; Fig. B1), as GPP can also be a proxy for root exudation and correlates with increased wetland CH_4 emissions (Knox et al., 2021; Whiting & Chanton, 1993). In addition, in a separate study within the same productive season, shrubs and graminoids were found to release more root-derived carbon at the end of the season (Mollenkopf et al., 2026). However, the biomass-weighted SRL trends were negative, which could result from species-specific SRL variation and the heterogeneous herbaceous root system (Gao et al., 2024; Picon-Cochard et al., 2011). The stronger negative trends in the beginning of the productive season may arise from increased plant carbon investment into herbaceous root growth in comparison with shrubs (Billings et al., 1978; Kummerow & Russell, 1980; Wang et al., 2016). However, within the intact and partly thawed stages and in a mixture of herbaceous and shrub plants, the SRL- CH_4 flux trends could in fact be positive (Fig. 3, B6), but inferential statistics with larger sample sizes per thaw stage are required to investigate this further. As temporal variation in SRL and its relationship with root exudation can be negligible throughout growing season (Gao et al., 2024) and studies in (sub)arctic peatlands are lacking (Iversen et al., 2015), the negative trends between biomass-weighted SRL and CH_4 fluxes across the thaw gradient remain uncertain.

625 Taken together, the temporal variation in root and rhizome traits may have contributed to CH_4 fluxes but belowground trait sampling with larger sample sizes throughout the productive season is needed to investigate these relationships further. Given the uncertain herbaceous SRL and root diameter relationships, future studies could benefit from separating the roots into coarse and fine fractions, measuring the associated root exudation rates, and utilizing minirhizotrons (Iversen et al., 2012; Phillips et al., 2008) to disentangle the temporal variation in root carbon substrate provision and CH_4 transport across the permafrost thaw gradient.

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5 Conclusions

Permafrost thaw alters peatland methane (CH₄) fluxes through changes in soil anoxia, nutrient and labile carbon availability, and vegetation composition. Here, we ~~focused on the influence of vegetation shift from shrub to herbaceous-dominated communities by exploring~~ the relationships between ~~community-level (herbaceous and shrub) plant belowground (root and rhizome) traits and CH₄ fluxes along a permafrost thaw gradient in a subarctic peatland. The belowground traits reflected the vegetation community shifts~~ along the thaw gradient from shrub- to herbaceous-dominated, with decreasing shrub belowground biomass and root tissue density with increasing thaw along the thaw gradient. Root tissue density showed a strong negative correlation with ~~was strongly and negatively correlated~~ with CH₄ fluxes, and increasing herbaceous rhizome surface area was associated with higher CH₄ fluxes. These relationships indicated increasing plant-mediated CH₄ transport with thaw, which was supported by lower pore water CH₄ concentrations in the fully thawed stage. Simultaneously, shrub specific root length (SRL) was positively, and root diameter negatively related with CH₄ fluxes, suggesting increased labile carbon substrate provision for acetoclastic methanogenesis. The relationships did not vary strongly during the productive season, but this was likely a result of the static belowground trait data values, warranting further temporal trait sampling.

We encourage further observational and experimental research particularly into the relationships between root and rhizome tissue density, SRL and CH₄ fluxes. The observed relationships could be further investigated with larger sample sizes and by combining temporal root trait sampling, root separation into fine and coarse fractions, and root exudation measurements to especially quantify the relationship between SRL and root exudation. Nonetheless, as root and rhizome trait data are scarce particularly from permafrost peatlands, and as the contribution of roots and rhizomes on plant-mediated CH₄ fluxes is understudied, this study provided valuable belowground proxies for plant-mediated CH₄ transport and fluxes. These proxies can inform future observational and experimental studies, as well as process-based wetland models by improving parameterization particularly related to plant-mediated CH₄ transport and helping fill gaps in our understanding of plant-mediated CH₄ cycling.

6 Appendices

Appendix A: Texts

Text Supplementary Methods A1: Vegetation surveys

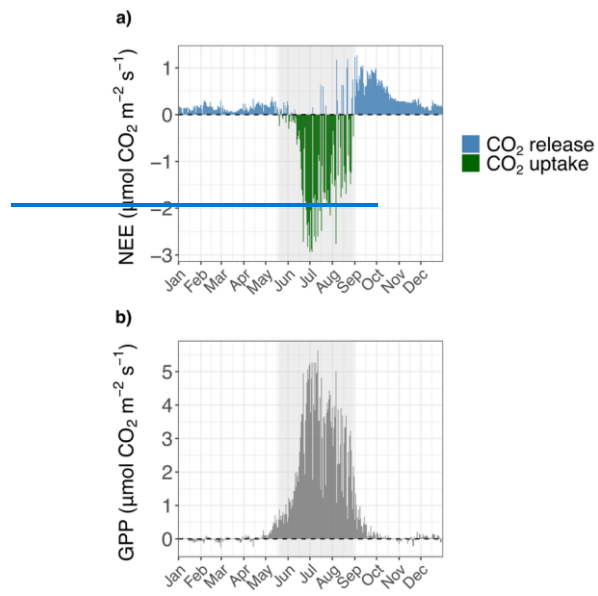
To evaluate the similarity between the CH₄ flux chamber plots and peat core plots, we conducted vegetation surveys using the point-intercept method on July 19th-23rd 2023. We used a 1.01 m² survey grid divided into 36 subquadrats (16.8 cm x 16.8 cm = 0.03 m²) and 25 intercept points. We lowered a dowel (60 cm long, 0.5 cm diameter) at each intercept point and noted the presence (i.e., “hit”) of each vascular plant and moss species that the dowel touched. At the peat core plots, the grid was always positioned towards northeast from the measurer and with the core in the middle of the grid. At the chamber plots, the grid was

positioned so that the chamber collar was approximately in the middle of the northeast edge of the grid (due to the chamber structure, we were unable to set the collar perfectly in the middle of the grid). The ground cover (e.g., litter and water), plant and moss species were surveyed separately. For ground cover data, if the measuring dowel hit multiple classes, only the class that touched the dowel first was recorded. Species and ground cover percentages were obtained by dividing the sum of hits for a species, vegetation (herbaceous, shrub and moss) or ground cover class by the total number of intercepts (n=25), multiplied by 100.

Supplementary Methods Text A2: Chamber CH₄ flux analyses

The fully thawed permafrost stage had the highest CH₄ flux (season median=75.2 mg CH₄ m⁻² d⁻¹, IQR=60.662 mg CH₄ m⁻² d⁻¹), followed by partly thawed stage (season median=30.0 mg CH₄ m⁻² d⁻¹, IQR=33.6-32.3 mg CH₄ m⁻² d⁻¹) but CH₄ fluxes at partly and fully thawed stages did not differ significantly (p>0.05). Intact stage had the lowest CH₄ fluxes (overall season median=0.3 mg CH₄ m⁻² d⁻¹, IQR=2.129 mg CH₄ m⁻² d⁻¹, p<0.015). At all thaw stages, CH₄ flux increased from the beginning to the end of the productive season: the maximum monthly median CH₄ fluxes were observed in August (max CH₄ flux: fully thawed 375.9 mg CH₄ m⁻² d⁻¹, partly thawed 160.4 mg CH₄ m⁻² d⁻¹, intact 96.4 mg CH₄ m⁻² d⁻¹), while minima were reached in June at intact (-1.9 -5.6 mg CH₄ m⁻² d⁻¹) and fully thawed (10.3 mg CH₄ m⁻² d⁻¹) stages, and in -and June-May at the partly thawed stage (2.0-1.54 mg CH₄ m⁻² d⁻¹) and fully thawed (11.59 mg CH₄ m⁻² d⁻¹) stages. In general, variation in CH₄ flux (coefficient of variation, CV) was larger between thaw stages (94.81%; May: 109.5%, August: 76.9%) than within them but the intact stage had large within-stage CH₄ flux variation (148.06%) which increased from May and June (125.58% and 124%, respectively) to August (165.33%), while the other stages had relatively low variation (partly thawed: 37.4%, fully thawed: 29.7%).

Appendix B: Figures



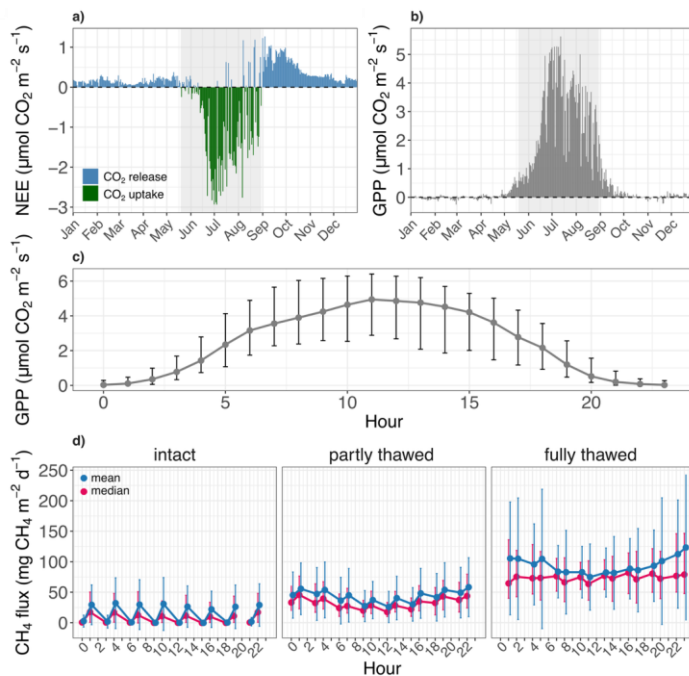


Figure B1: Daily net ecosystem CO₂ exchange (NEE; $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) (a) and gross primary production (GPP; $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) (b), and hourly GPP and CH₄ fluxes during the productive season in 2023. a) The productive season was defined as the period between the first and last passing of daily median NEE past zero (highlighted in gray; 19th of May 2023 to 30th of August 2023) (Körner et al., 2023). b) Daily median GPP (based on nighttime partitioning) is shown for reference as a proxy for plant-mediated carbon substrate provision at the ecosystem scale (Knox et al., 2021). c) Hourly GPP medians (based on daytime partitioning with light response curves for better estimation of diurnal trends). The error bars represent the ranges between 25th and 75th percentiles around the hourly medians. d) Hourly CH₄ flux medians (in red) and means (in blue) at each permafrost thaw stage. The error bars represent the ranges between 25th and 75th percentiles around the hourly medians. Hourly means are shown in addition to medians to reflect short-term CH₄ pulses at the diurnal scale. NEE and GPP data: Lundin et al., 2025. Note that the NEE and GPP data likely mostly originate from intact and partly thawed permafrost stages and do not cover the fully thawed stage (Łakomiec et al., 2021).

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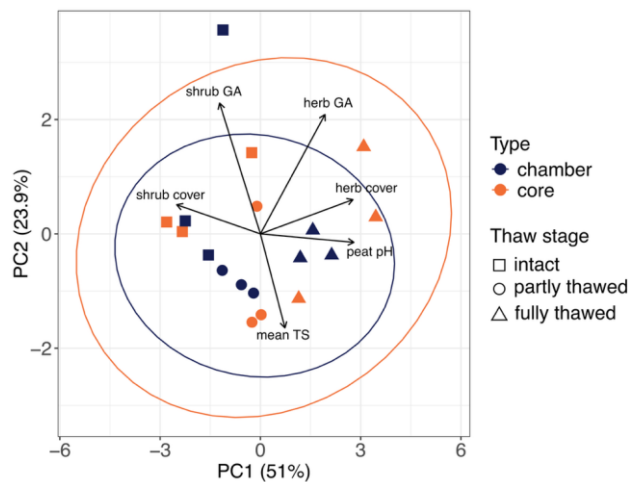


Figure B2: The similarity of peat core (n=9) and automated chamber CH₄ flux measurement (n=9) plots based on principal component analysis (PCA). In the figure, chamber and core plots are represented by dark purple and orange points, respectively, while thaw stages are shown in different shapes (rectangle = intact permafrost, circle = partly thawed permafrost, triangle = fully thawed permafrost). The ellipses represent 95% data ellipses for the chamber and core plots within the multivariate space defined by the first two principal components (chamber = dark purple, orange = core). The PCA was based on normalized plot herbaceous and shrub plant cover and green area (GA), mean [soil-peat](#) temperature (mean TS) and peat or porewater pH (here, referred to as peat pH), using function PCA from package FactoMineR (Lê et al., 2008) (results shown in the figure). In addition, we used PERMANOVA with function adonis2 from package vegan (Oksanen et al., 2025) and Euclidean distances between plots within thaw stages to estimate the similarity between core and chamber plots based on the same environmental variables. Based on these assessments, the peat core plots had a larger spread in multivariate space than CH₄ flux plots mostly due to slightly higher shrub or herbaceous plant cover in one plot within each thaw stage, but the differences were not significant with the sample size n=9 (p=0.94). Thus, the root and rhizome measurements could be used to roughly represent belowground traits in the CH₄ flux measurement plots. However, we acknowledge that the measured root and rhizome traits do not exactly correspond to those within the CH₄ flux plots and took this into account in the result interpretation.

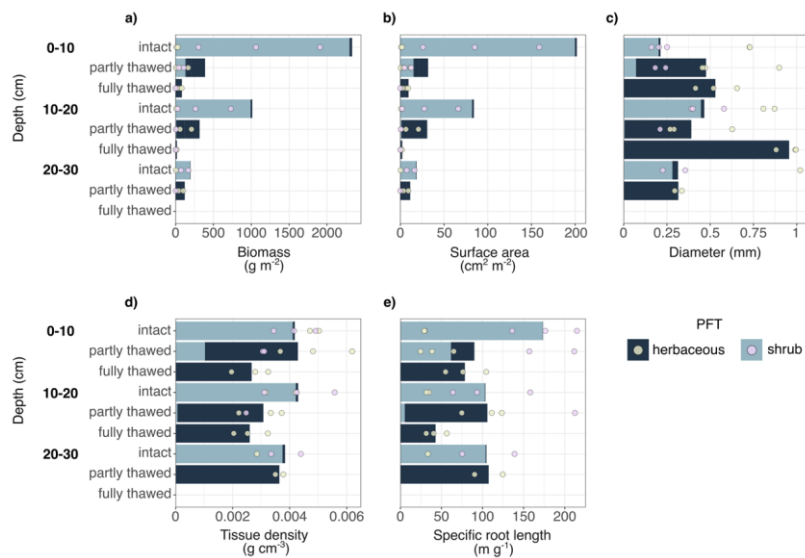


Figure B3: Root traits across the depth profile (0-10, 10-20, 20-30 cm) per thaw stage and plant functional type (PFT). The stacked bar colors (dark blue: herbaceous, light blue: shrub) represent the proportion of the PFT on the total biomass (a) or surface area (b), or the contribution of each PFT on the biomass-weighted trait mean (c-e). The points (light green: herbaceous, light purple: shrub) represent depth-per-plot measurements. a-b) and e) Root biomass, surface area and length were standardized to 10 cm depth increments. c-e) Biomass-weighted trait means.

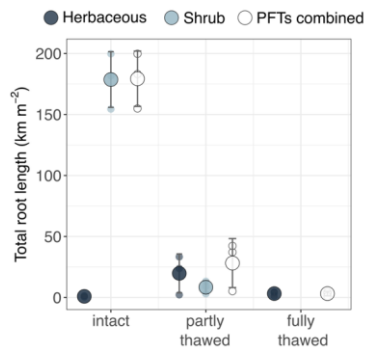


Figure B4: Root total length (km m^{-2}) across thaw stages per and across plant functional types (PFT). Large points indicate thaw stage mean and small points plot-scale measurements. Colors indicate PFTs (dark grey: herbaceous, light grey: shrub, white: PFTs summed). Error bars represent 1 standard deviation of the mean. Root total length was standardized to 30 cm depth in all plots.

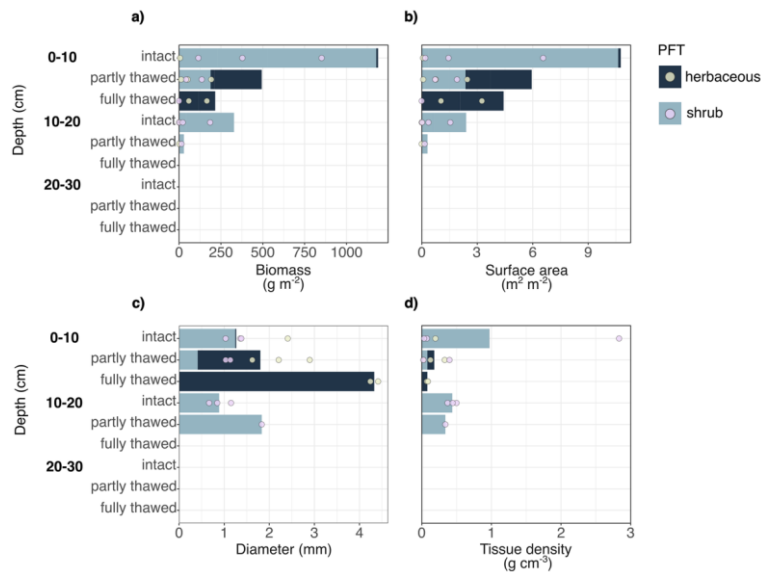
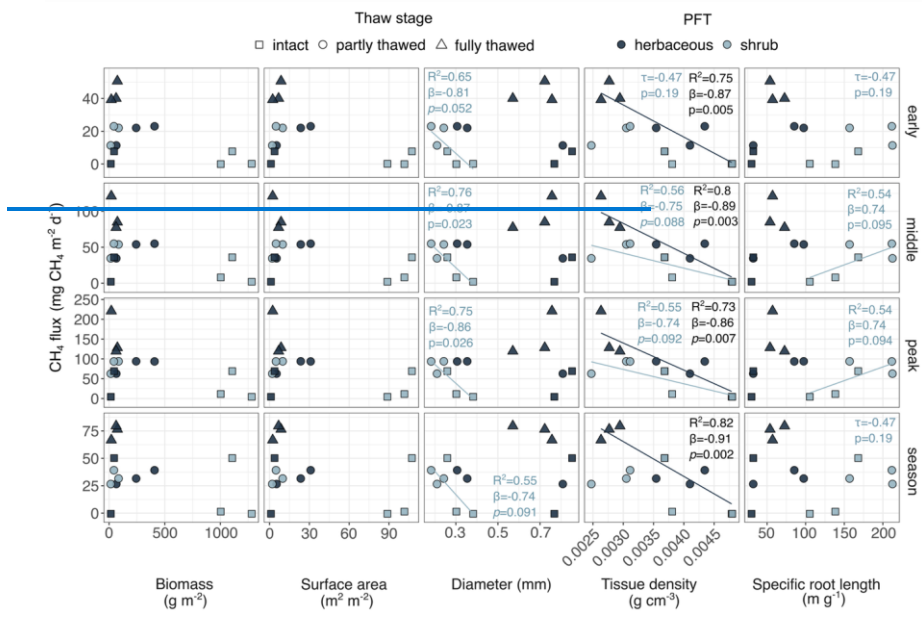


Figure B5: Rhizome traits across the depth profile (0-10, 10-20, 20-30 cm) per thaw stage and plant functional type (PFT). The stacked bar colors (dark blue: herbaceous, light blue: shrub) represent the proportion of the PFT on the total biomass (a) or surface

725 area (b), or the contribution of each PFT on the biomass-weighted trait mean (c-d). The points (light green: herbaceous, light purple: shrub) represent depth-per-plot measurements. a-b) and e) Root biomass, surface area and length were standardized to 10 cm depth increments. c-d) Biomass-weighted trait means.



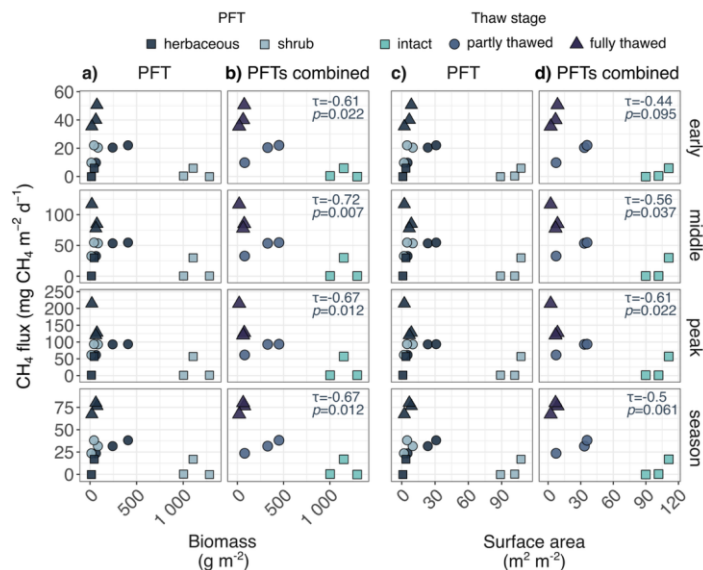


Figure B6: Relationship between root traits-biomass (columns a-b), surface area (columns c-d) and all-CH₄ fluxes season values (early, middle, peak and season; rows). a and c) Relationships between root traits and CH₄ fluxes per plant functional type (PFT), where dark gray: herbaceous plants, light gray: shrubs. B and d) Relationships between root traits and CH₄ fluxes across PFTs (biomass and surface area summed), where light blue rectangle: intact, gray circle: partly thawed, and dark purple triangle: fully thawed stage. Kendall's τ is shown for relationships where $\tau \geq 0.2$ (note that due to the low sample size, p-values should be interpreted with caution). Linear regression model assumptions were not met for any of the relationships.

The different point shapes represent thaw stages (rectangle = intact permafrost, circle = partly-thawed permafrost, and triangle = fully-thawed permafrost), while colors represent plant functional types (PFT) (dark blue = herbaceous, light blue = shrub). Lines represent linear regression fit for visualization, while R^2 and effect size (β) are based on linear regressions with centered and scaled trait and CH₄ flux values (lines, R^2 and β are only shown when $R^2 > 0.2$, model $p < 0.1$, and the linear

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740 regression model assumptions were met). Kendall's τ is shown for relationships where linear regression model assumptions
 745 were not met and $\tau > 0.2$ (note that due to sample $n=9$, the correlation p -values should be interpreted with caution).

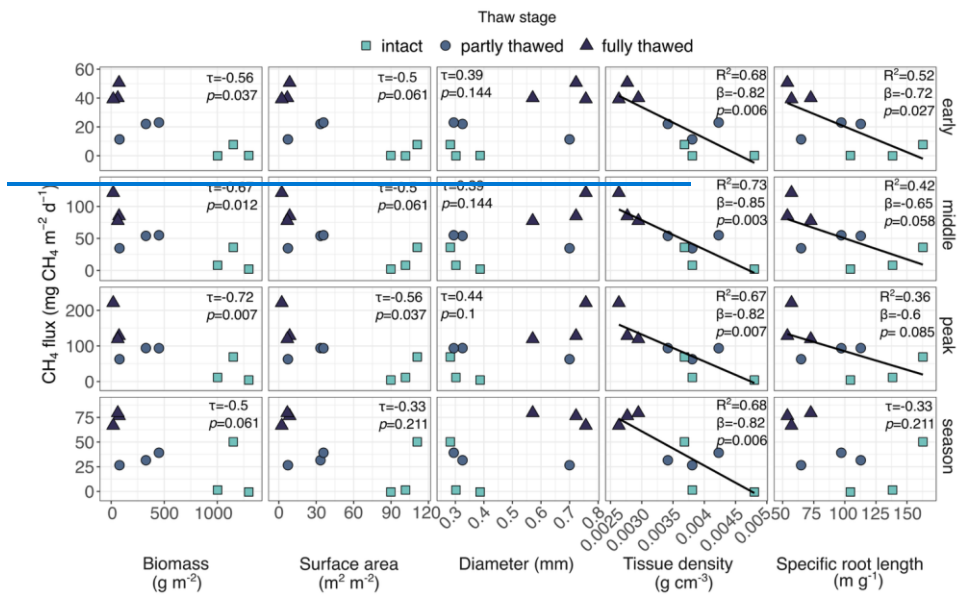
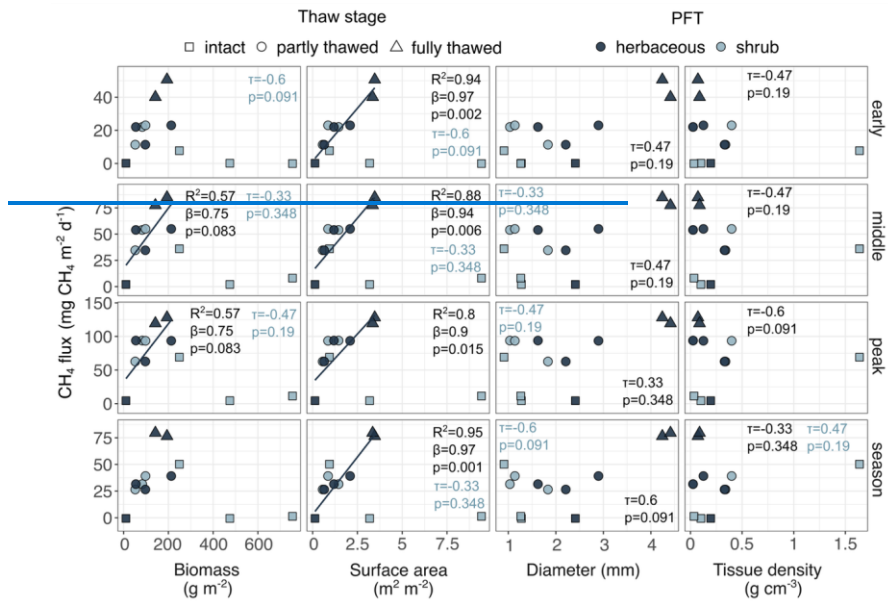


Figure B7: Relationship between root traits (columns) and CH₄ flux season-values (rows) with plant functional types (PFT) averaged (root diameter, tissue density, and specific length; weighted mean using root biomass) and summed (root biomass and surface area). The lines represent linear regression fit used for visualization, while R² and effect size (β) are reported for linear regressions with centered and scaled CH₄ flux and trait values. Point shapes and colors represent different thaw stages (light blue rectangle = intact permafrost, dark blue circle = partly thawed permafrost, purple triangle = fully thawed permafrost). Kendall's τ is shown for relationships where linear regression model assumptions were not met and $\tau > 0.2$ (note that due to sample $n=9$, the correlation p -values should be interpreted with caution).



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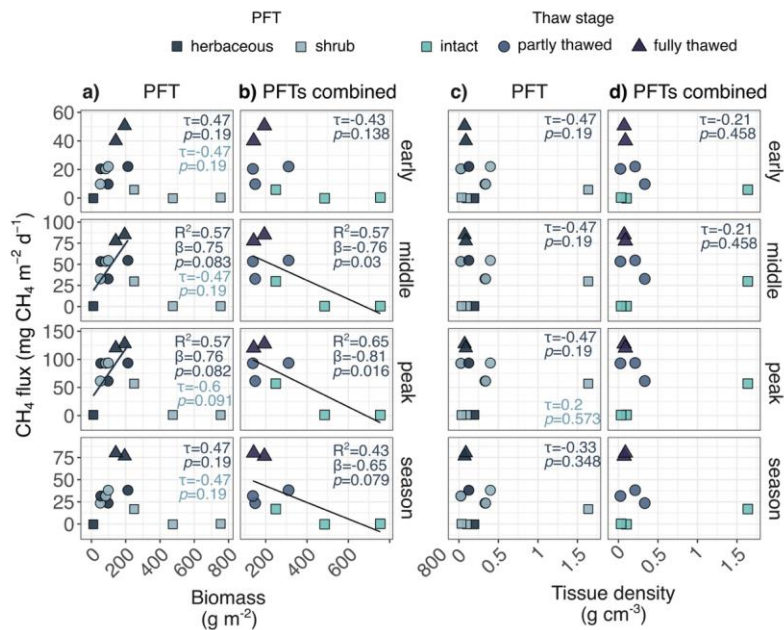


Figure B78: Relationship between rhizome biomass (columns a-b), tissue density (columns c-d) and CH_4 fluxes (early, middle, peak, and season; rows). a and c) Relationships between rhizome traits and CH_4 fluxes per plant functional type (PFT), where dark gray: herbaceous plants, light gray: shrubs. b and d) Relationships between rhizome traits and CH_4 fluxes across PFTs (summed biomass, biomass-weighted tissue density), where light blue rectangle: intact, gray circle: partly thawed, and dark purple triangle: fully thawed stage. The lines represent linear regression fit used for visualization, while R^2 and effect size (β) are reported for linear regressions with centered and scaled CH_4 flux and trait values (when $R^2 > 0.2$, model $p < 0.1$, and linear regression model assumptions were met). Kendall's τ is shown for relationships where $\tau > 0.2$ (note that due to the low sample size, p-values should be interpreted with caution). Relationship between rhizome traits (columns) and all CH_4 flux season values (rows). The different point shapes represent thaw stages (rectangle = intact permafrost, circle = partly thawed permafrost, and triangle = fully thawed permafrost), while colors represent plant functional types (PFT; dark blue = herbaceous, light blue = shrub). Lines represent linear regression fit for visualization, while R^2 and effect size (β) are based on linear regressions with centered and scaled trait and CH_4 flux values (lines, R^2 and β are only shown when $R^2 > 0.2$, model $p < 0.1$, and the linear regression model assumptions were met). Kendall's τ is shown for relationships where linear regression model assumptions were not met and $\tau > 0.2$ (note that due to sample $n=9$, the correlation p-values should be interpreted with caution).

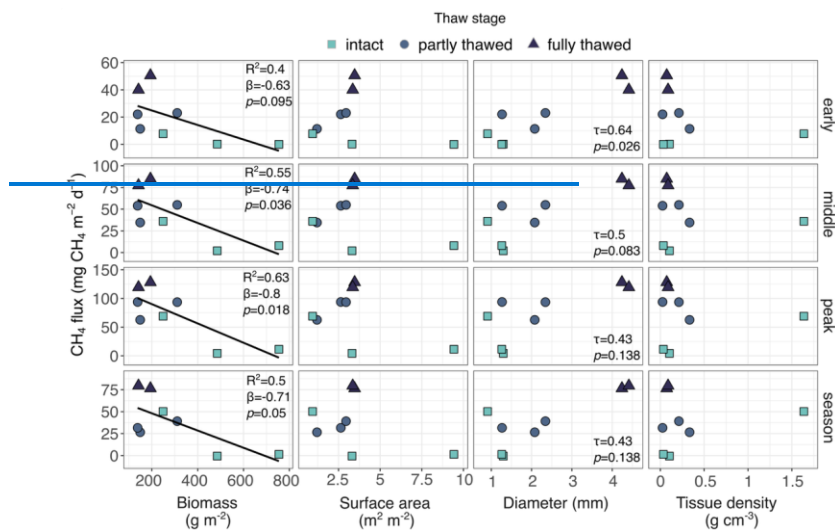


Figure B9: Relationship between rhizome traits (columns) and CH₄ flux season values (rows) with plant functional types (PFTs) averaged (rhizome diameter and tissue density; weighted mean using rhizome biomass) and summed (rhizome biomass and surface area). The lines represent linear regression fit used for visualization, while R^2 and effect size (β) are reported for linear regressions with centered and scaled CH₄ flux and trait values (when $R^2 > 0.2$, model $p < 0.1$, and linear regression model assumptions were met). Point shapes and colors represent different thaw stages (light blue rectangle = intact permafrost, dark blue circle = partly thawed permafrost, purple triangle = fully thawed permafrost). Kendall's τ is shown for relationships where linear regression model assumptions were not met and $\tau > 0.2$ (note that due to sample $n=9$, the correlation p -values should be interpreted with caution).

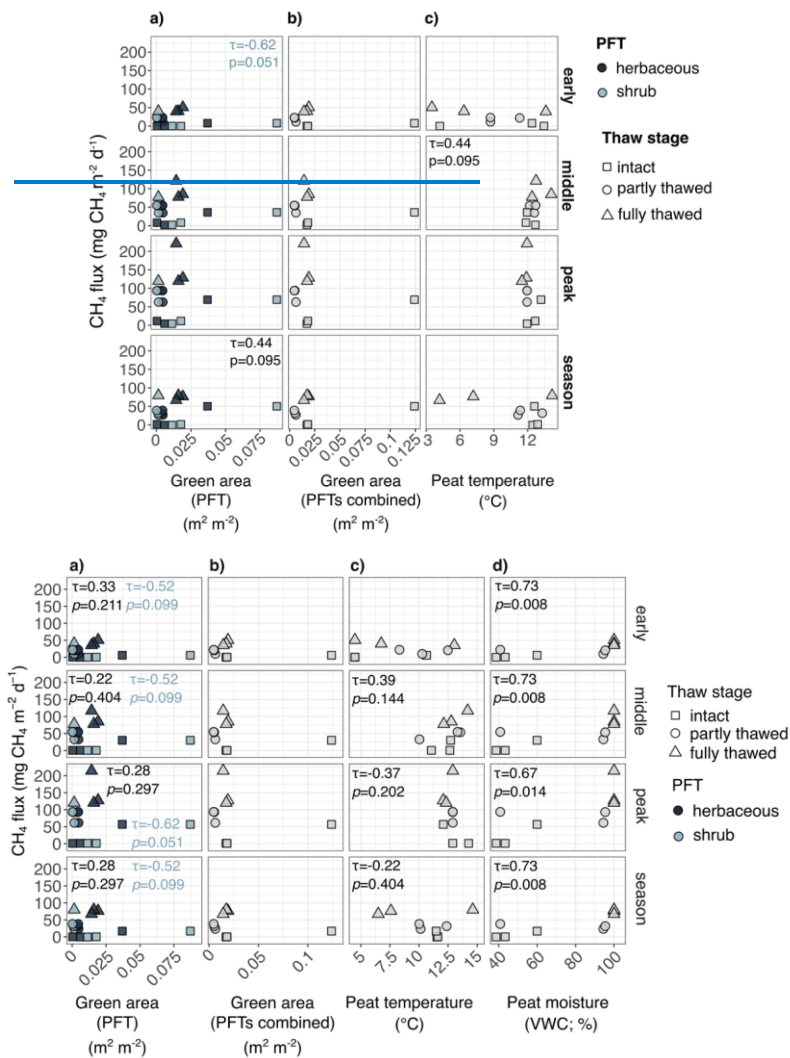


Figure B810: Relationship between plant functional type (PFT)-specific plant green area (column a), plant green area summed across PFTs (column b), soil-peat temperature (column c), peat moisture (volumetric water content VWC; column d), and CH₄ flux

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season values (rows). Kendall τ correlation coefficient (τ) is reported for the relationship when $p \leq 0.1$ and $\tau > 0.2$ (note that due to sample $n=9$, the correlation p -values should be interpreted with caution). The different point shapes represent thaw stages (rectangle = intact permafrost, circle = partly thawed permafrost, and triangle = fully thawed permafrost). a) Colors represent different PFTs (dark blue = herbaceous [plants](#), light blue = shrubs).

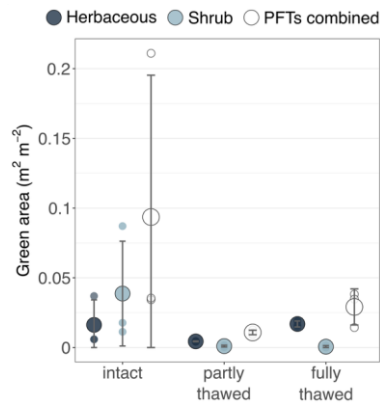


Figure B244: The plant green area (GA; $\text{m}^2 \text{m}^{-2}$) varied slightly between thaw stages. Large points represent group means, small points plot-scale measurements, and error bars ± 1 standard deviation. The colors represent plant functional type (PFT) groups: dark grey is herbaceous, light grey is shrub, and white is the sum of PFT GAs. Herbaceous GA coefficient of variation (CV) was highest within intact permafrost (137%), while shrub GA varied most within intact permafrost (109%). Note that shrubs (*Betula nana*) were only found in one plot and were only 3% of the total GA in the fully thawed permafrost stage.

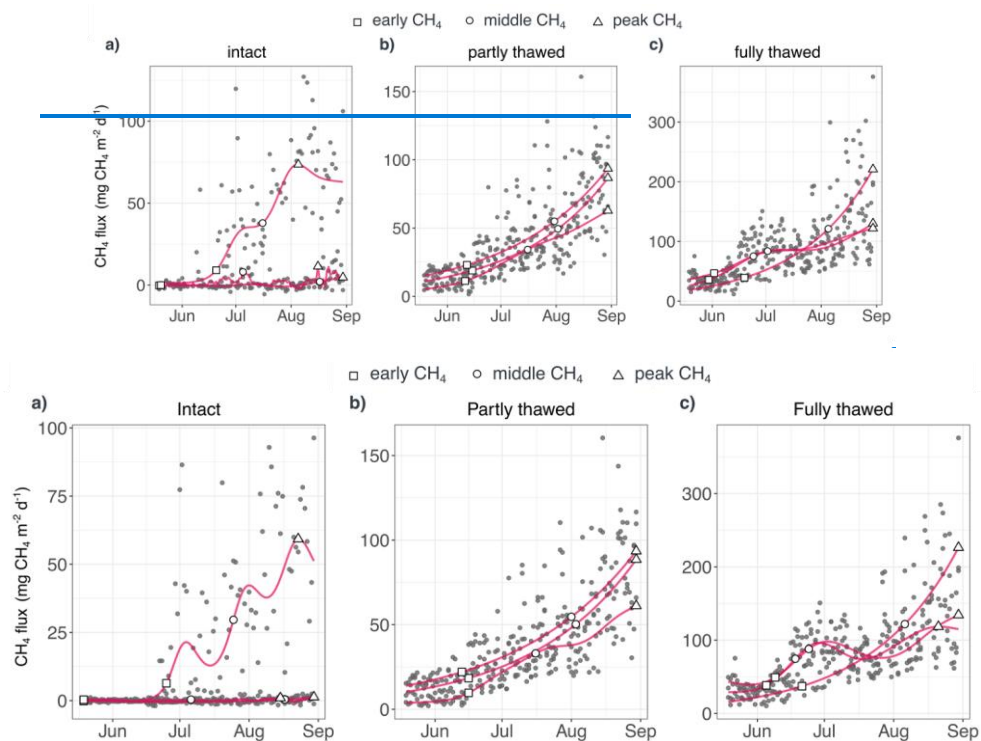
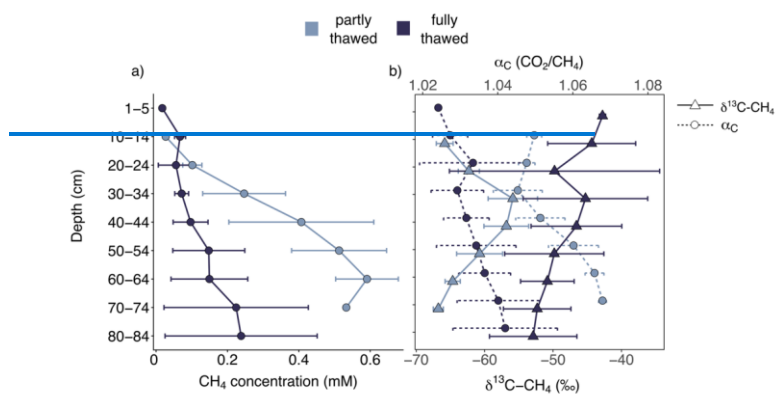


Figure B102: Daily median CH₄ flux with CH₄ flux period values over the productive season at intact (a), partly thawed (b) and fully thawed (c) stages. a-c) Red lines represent chamber-specific GAM fit ($R^2 \geq 0.32$), except for one chamber in a) where GAM $R^2 < 0.1$, and the line represents the moving 7-day median CH₄ flux. Squares represent early, circles middle and triangles peak CH₄ flux season. See chamber GAM R^2 in Table C5.



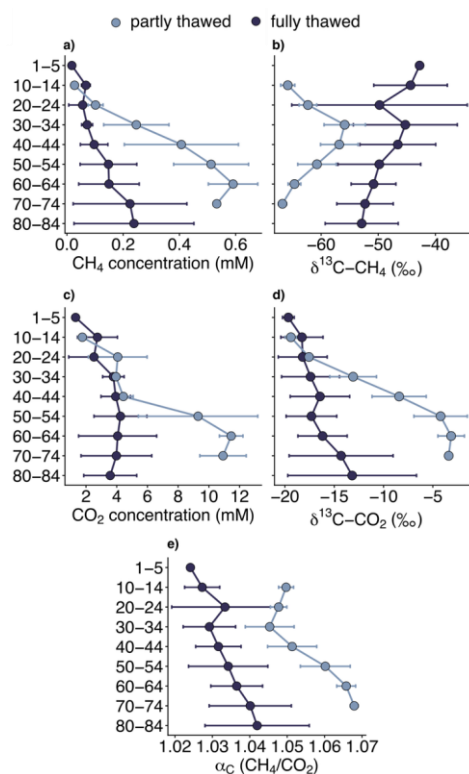


Figure B113: Porewater CH₄ concentration (mM) (a), δ¹³C-CH₄ (‰) (b), CO₂ concentration (c), δ¹³C-CO₂ (‰) (d), and carbon isotope fractionation factor (α_C CO₂/CH₄) (e) from peat surface to 84 cm depth at partly and fully thawed permafrost stages. Line and point colors represent thaw stages. a) Porewater CH₄ concentration, b) Top x-axis: α_C (dashed lines with triangles), where higher values indicate larger fractionation (i.e., more hydrogenotrophy) and vice versa (i.e., more acetoclasty), bottom x-axis: δ¹³C-CH₄ (solid lines with circles), α_C and δ¹³C-CH₄ lines have been slightly shifted vertically for visualization. Briefly, mean CH₄ concentrations increased from 0.027 ± 0.004 (standard deviation) mM to 0.533 ± 0.0007 mM at 70-74 cm depth at the partly thawed stage and from 0.017 ± 0.007 mM to 0.238 ± 0.213 mM at 80-84 cm depth at the fully thawed stage. δ¹³C-CH₄ values became enriched at ca. 30-44 cm (partly thawed ca. -56.4 ‰, fully thawed ca. -46 ‰), and this enrichment was associated with a decrease in α_C (ca. 1.048 partly thawed, ca. 1.03 fully thawed). Mean CO₂ concentrations increased from 1.758 ± 0.284 mM to 11.454 ± 0.766 at 60-64 cm depth and 10.923 ± 1.51 at 70-74 cm depth at the partly thawed stage (with a decrease at 30-44 cm depth, with means of 3.951 and 4.430 mM), and from 1.322 ± 0.089 mM to 3.576 ± 1.725 mM at 80-84 cm at the fully thawed stage. δ¹³C-CO₂ became more enriched with depth particularly at the partly thawed stage (from -19.398 ‰ to -3.394 ‰).

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Appendix C: Tables

Table C1: Plant cover (%) by species and herbaceous and shrub vegetation classes, litter and water surface cover (%), and peat characteristics in each chamber and peat coring (“core”) plot (as peat cores were selected to represent each individual chamber, the core and chamber plots have the same ID number). Note that the intact 1 chamber plot was on a collapsing palsa. Chamber plot WTD is the mean annual WTD across the 2007-2017 period per thaw stage (Crill et al., 2023). Values after “±” are one standard deviation of the mean. WTD = water table depth (cm; from the peat surface).

Plot	Species	Plant cover (%)		Litter and water cover (%)		Mean soil temp (°C)		pH		WTD (cm)		Active layer depth (cm)	
		Chamber	Core	Chamber	Core	Chamber	Core	Chamber	Core	Chamber	Core	Chamber	Core
Intact 1	<i>Eriophorum vaginatum</i>	48	28	Litter: 20	Litter: 16	9.52 ± 0.98	9.34 ± 1.54	3.1	3.0	-	-	47	37.5
	<i>Vaccinium uliginosum</i>	48	28										
	<i>Andromeda polifolia</i>	32	24	Water: 0	Water: 0								
	<i>Empetrum nigrum</i>	24	56										
	<i>Rubus chamaemorus</i>	0	8										
	<i>Vaccinium vitis-idaea</i>	0	4										
	<i>Dicranum</i> sp.	8	52										
	<i>Polytrichum</i> sp.	4	0										
	Shrub	104	120										
	Herbaceous	48	28										
Intact 2	<i>A. polifolia</i>	52	48	Litter: 28	Litter: 16	7.7 ± 0.6	7.7 ± 1.1	3.1	3.0	-	-	41.5	39
	<i>E. nigrum</i>	16	16										
	<i>R. chamaemorus</i>	4	32										
	<i>V. uliginosum</i>	4	0	Water: 0	Water: 0								
	<i>Carex rotundata</i>	4	0										
	<i>Betula nana</i>	0	28										
	<i>V. vitis-idaea</i>	0	4										
	<i>E. vaginatum</i>	0	4										
	<i>Ptilidium ciliare</i>	48	20										
	<i>Dicranum</i> sp.	8	20										
	Shrub	76	128										
	Herbaceous	4	4										
Intact 3	<i>E. vaginatum</i>	84	92	Litter: 0	Litter: 4	8.7 ± 0.8	8.3 ± 1.9	2.8	3.2	-	-	-	85
	<i>V. uliginosum</i>	24	20										
	<i>R. chamaemorus</i>	16	4										
	<i>E. nigrum</i>	12	20	Water: 12	Water: 0								
	<i>A. polifolia</i>	8	8										
	<i>B. nana</i>	8	12										
		32	0										

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	<i>Sphagnum balticum</i>	0	8										
	<i>Dicranum</i> sp.	84	92										
	Herbaceous	68	64										
	Shrub												
Partly thawed	<i>C. rotundata</i>	52	0	Litter	Litter:	9.5 ±	7.0	3.3	3.2	-9.1 ±	-	>85	>85
12	<i>E. vaginatum</i>	0	80	: 0	0	0.6	±			4.6	14.767		
	<i>S. capillifolium</i>	100	100				1.2						
	Herbaceous	52	80	Water:	Water:								
	Shrub	0	0	r: 0	0								
Partly thawed	<i>C. rotundata</i>	52	60	Litter	Litter:	9.1 ±	10.9	3.2	3.8	-9.1 ±	-21	>85	>85
24	<i>V. oxycoccus</i>	48	20	: 16	20	0.5	±			4.6			
	<i>A. polifolia</i>	28	24				1.03						
	<i>E. angustifolium</i>	0	8	Water:	Water:								
	<i>E. vaginatum</i>	0	4	r: 0	0								
	<i>Drosera rotundifolia</i>	0	4										
	<i>S. capillifolium</i>	100	72										
	<i>P. ciliare</i>	0	16										
	Herbaceous	52	76										
	Shrub	76	44										
Partly thawed	<i>V. oxycoccus</i>	16	36	Litter	Litter:	9.1 ±	10.9	3.3	3.4	-9.1 ±	-27	>85	>85
36	<i>C. rotundata</i>	40	36	: 44	8	0.6	±			4.6			
	<i>E. angustifolium</i>	0	24				0.7						
	<i>S. capillifolium</i>	88	96	Water:	Water:								
	Herbaceous	40	60	r: 0	0								
	Shrub	40	36										
Fully thawed	<i>E. angustifolium</i>	96	100	Litter	Litter:	9.7 ±	8.7	5.1	5.7	2.1 ±	0	>85	>85
17	<i>Equisetum fluviatile</i>	40	20	: 0	4	0.3	±			4.4			
	Herbaceous	136	120	Water:	Water:		0.4						
	Shrub	0	0	r: 12	0								
Fully thawed	<i>E. angustifolium</i>	88	100	Litter	Litter:	8.4 ±	9.6	5.0	6.0	2.1 ±	0	>85	>85
28	<i>E. fluviatile</i>	24	68	: 0	0	1.0	±			4.4			
	<i>Comarum palustre</i>	4	12				0.3						
	<i>S. riparium</i>	12	0	Water:	Water:								
	Herbaceous	116	180	r: 0	0								
	Shrub	0	0										
Fully thawed	<i>E. angustifolium</i>	92	84	Litter	Litter:	9.1 ±	10.1	4.7	4.8	2.1 ±	0	>85	>85
39	<i>S. riparium</i>	40	96	: 0	24	0.3	±			4.4			
	Herbaceous	92	84				0.4						
	Shrub	0	0	Water:	Water:								
				r: 0	0								

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Table C2: Species included in the vegetation green area (GA) measurements per thaw stage. Mean GA (with standard deviation) is reported for each species across the three plots per thaw stage, and comprises the sum of stem and leaf green area (m² m⁻²).

Thaw stage	Species	Mean GA (m ² m ⁻²)
Intact	<i>Andromeda polifolia</i>	0.1083 ± 0.06
	<i>Betula nana</i>	0.0243 ± 0.02
	<i>Carex rotundata</i>	0.00988 ± 0
	<i>Empetrum nigrum</i>	0.0833 ± 0.07
	<i>Eriophorum vaginatum</i>	0.4792 ± 0.54
	<i>Rubus chamaemorus</i>	0.160599 ± 22.34
	<i>Vaccinium uliginosum</i>	0.190899 ± 0.25
	<i>Vaccinium vitis-idaea</i>	0.005 ± 0.004
Partly thawed	<i>Andromeda polifolia</i>	0.03549 ± 0.04
	<i>Betula nana</i>	0.0162 ± 0.02
	<i>Carex rotundata</i>	0.16329 ± 0.07
	<i>Drosera rotundifolia</i>	0.0014 ± 0
	<i>Empetrum nigrum</i>	0.0293 ± 0
	<i>Eriophorum angustifolium</i>	0.05437 ± 0
	<i>Eriophorum vaginatum</i>	0.31659 ± 0.16
	<i>Rubus chamaemorus</i>	0.0263 ± 0
	<i>Vaccinium oxycoccos</i>	0.0113 ± 0.01
Fully thawed	<i>Vaccinium uliginosum</i>	0.00109 ± 0
	<i>Betula nana</i>	0.0104 ± 0
	<i>Carex canescens</i>	0.00329 ± 0
	<i>Comarum palustre</i>	0.0864 ± 0.06
	<i>Equisetum fluviatile</i>	0.89658 ± 0.63
	<i>Eriophorum angustifolium</i>	0.65107 ± 0.64
	<i>Galium palustre</i>	0.0124 ± 0

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Table C3: Peat moisture data aggregated to daily medians from May-August periods in 2024 and 2025. Peat moisture was measured as volumetric water content (VWC, %) at each chamber. Date is expressed as YYYY-MM-DD.

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2025-08-04	9	fully thawed	100
2025-08-05	9	fully thawed	100
2025-08-06	9	fully thawed	100
2025-08-07	9	fully thawed	100
2025-08-08	9	fully thawed	100
2025-08-09	9	fully thawed	100
2025-08-10	9	fully thawed	100
2025-08-11	9	fully thawed	100
2025-08-12	9	fully thawed	100
2025-08-13	9	fully thawed	100

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Table C43: Vascular plant species growing directly on the peat cores and their leaf, stem, and flower biomass. As peat cores were selected to represent each individual chamber, the core and chamber plots have the same ID number. Note that the biomass estimates are likely underestimations due to some plant material being lost in the field. We show this table primarily for the species list.

Plot	Species	Biomass (g)			Total
		Leaf	Stem	Flower	
Intact 1	<i>E. vaginatum</i>	0.06741	0.00309	0	0.07105
	<i>V. uliginosum</i>	0.136576	0.55449	0	0.69025
	<i>E. nigrum</i>	0.02116	0.02316	0	0.04432
	<i>A. polifolia</i>	0.07106	0.048793	0	0.119899
	<i>R. chamaemorus</i>	0.032169	0.008783	0	0.040952
Intact 3	<i>V. uliginosum</i>	0.01615	0.091976	0	0.107691
	<i>E. nigrum</i>	0.09819	0.152203	0	0.250393
	<i>A. polifolia</i>	0.24815	0.33348	0	0.582163
	<i>E. vaginatum</i>	0.009862	0	0	0.009862
Intact 5	<i>E. vaginatum</i>	0.5163	0.04528	0	0.562158
	<i>A. polifolia</i>	0.1009981	0.03223	0	0.13204
	<i>E. nigrum</i>	0.41146	0.534396	0	0.94542
	<i>V. uliginosum</i>	0.096566	0.36216	0	0.45726
	<i>V. oxycoccos</i>	0.01806	0.03149	0	0.0504955
Partly thawed 2	<i>E. vaginatum</i>	1.192198	0.45312	0.02525	1.67035
Partly thawed 4	<i>E. angustifolium</i>	0.00545	0.11216	0	0.11705
	<i>V. oxycoccos</i>	0.00636	0.0093	0	0.016566
	<i>A. polifolia</i>	0.0471	0.03144	0.008791	0.08645
	<i>C. rotundata</i>	0.0683	0.078754	0	0.146584
Partly thawed 6	<i>V. oxycoccos</i>	0.04531	0.04715	0	0.09246
	<i>C. rotundata</i>	0.50924	0.100	0.03343	0.643267
	<i>E. angustifolium</i>	0.11302	0.0605956	0	0.173258
Fully thawed 7	<i>E. angustifolium</i>	0.005481	0.00434	0	0.00915
Fully thawed 8	NA (only dead vegetation)	0	0	0	0
Fully thawed 9	<i>E. angustifolium</i>	0.01042	0	0	0.01042

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Table C54: Automated chamber CH₄ flux (mg CH₄ m⁻² d⁻¹) and peat temperature data aggregated to daily scale with medians (CH₄ flux) and means (CH₄ flux and peat temperature). Each thaw stage (intact, partly thawed and fully thawed permafrost) has three

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chambers, resulting in 9 chambers in total across the gradient. Date is reported as YYYY-MM-DD. Peat temperature was measured at each chamber in °C.

date	chamber_id	eh4_flux_mgch4m2d1	peat_temp	thaw_stage
2023-05-19	1	-1.5742155	3.7	intaet
2023-05-21	1	0.11011842	7.7	intaet
2023-05-22	1	-2.0749876	11.6	intaet
2023-05-23	1	2.73592456	9.8	intaet
2023-05-24	1	0.6504314	6.5	intaet
2023-05-25	1	-0.2753291	5.9	intaet
2023-05-27	1	-1.4930673	3.5	intaet
2023-05-28	1	0.53437161	7.25	intaet
2023-05-29	1	-0.8084409	NA	intaet
2023-05-30	1	-0.8862095	6	intaet
2023-05-31	1	-1.0112265	5.9	intaet
2023-06-01	1	-0.5574734	3.6	intaet
2023-06-02	1	-0.998409	4.7	intaet
2023-06-03	1	-0.376127	5.4	intaet
2023-06-04	1	-0.9622294	6	intaet
2023-06-10	1	-0.6405388	11.25	intaet
2023-06-11	1	58.2029094	10.5	intaet
2023-06-12	1	-1.0596144	9.8	intaet
2023-06-13	1	0.30756114	7.9	intaet
2023-06-14	1	-0.4510569	10.3	intaet
2023-06-16	1	-1.4557005	11.8	intaet
2023-06-17	1	-0.9726219	14.8	intaet
2023-06-18	1	-1.6011772	15.3	intaet
2023-06-19	1	-1.5296095	15.6	intaet
2023-06-20	1	-0.9589859	15.55	intaet
2023-06-21	1	0.33550547	15.1	intaet
2023-06-22	1	-0.653831	15.5	intaet
2023-06-23	1	-0.7277735	15.4	intaet
2023-06-24	1	-0.8945707	12.6	intaet
2023-06-25	1	-1.2535992	12.15	intaet
2023-06-26	1	-0.5782371	12.5	intaet
2023-06-27	1	-0.9384954	15.85	intaet
2023-06-28	1	-0.5582339	13.55	intaet
2023-06-29	1	6.13238862	16.3	intaet
2023-07-02	1	-1.7506662	11.45	intaet

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2023-07-03	+	-0.4727376	10.2	intact
2023-07-04	+	0.12544433	14.2	intact
2023-07-05	+	4.68531914	11.7	intact
2023-07-06	+	-1.5189094	12.2	intact
2023-07-08	+	0.85818027	14.8	intact
2023-07-09	+	-1.1912977	13.6	intact
2023-07-10	+	-1.7284981	18.1	intact
2023-07-11	+	24.6812614	17.3	intact
2023-07-14	+	-0.5412949	NA	intact
2023-07-15	+	0.135732	13	intact
2023-07-16	+	19.4200096	10.2	intact
2023-07-17	+	0.28613647	11.6	intact
2023-07-18	+	0.29784641	12.7	intact
2023-07-19	+	-2.4859508	11.9	intact
2023-07-20	+	-1.9277671	10.8	intact
2023-07-21	+	-2.1024176	12.4	intact
2023-07-23	+	1.34978199	10.6	intact
2023-07-24	+	-1.4619621	12.8	intact
2023-07-26	+	-1.0331124	NA	intact
2023-07-27	+	-1.8103016	17.45	intact
2023-07-29	+	-2.4061967	15.35	intact
2023-07-30	+	-2.8735807	13.75	intact
2023-08-01	+	0.81351311	13.75	intact
2023-08-02	+	0.96200058	13.8	intact
2023-08-03	+	-0.6077703	15.3	intact
2023-08-04	+	-1.471697	14.5	intact
2023-08-05	+	-0.1108434	12.75	intact
2023-08-06	+	-2.2913776	12	intact
2023-08-07	+	1.36918011	NA	intact
2023-08-08	+	-1.4553593	12.2	intact
2023-08-09	+	0.86322717	15.5	intact
2023-08-10	+	2.81393942	14.4	intact
2023-08-11	+	-1.3108983	13.2	intact
2023-08-12	+	1.56942242	14.4	intact
2023-08-13	+	112.869073	11.5	intact
2023-08-14	+	-1.3360591	14.2	intact
2023-08-15	+	2.17306634	14.05	intact
2023-08-16	+	1.08742737	12.7	intact
2023-08-17	+	-1.4419661	14.3	intact

2023-08-18	1	40.8011232	NA	intact
2023-08-19	1	10.2510742	10.05	intact
2023-08-20	1	0.99956116	11.6	intact
2023-08-22	1	3.08381065	12.8	intact
2023-08-23	1	4.17373264	13.8	intact
2023-08-24	1	-3.1773699	11.9	intact
2023-08-25	1	7.96674475	11.95	intact
2023-08-26	1	15.2623273	NA	intact
2023-08-27	1	20.5337876	NA	intact
2023-08-28	1	2.50175877	NA	intact
2023-08-29	1	3.97112172	NA	intact
2023-08-30	1	2.83833648	NA	intact
2023-05-19	2	4.54583509	3.3	partly_thawed
2023-05-20	2	7.69370639	4.2	partly_thawed
2023-05-21	2	5.64355684	4.7	partly_thawed
2023-05-22	2	9.71601188	4.8	partly_thawed
2023-05-23	2	9.48145508	5.65	partly_thawed
2023-05-24	2	11.003204	4.8	partly_thawed
2023-05-25	2	5.37497615	4.4	partly_thawed
2023-05-26	2	7.53370138	2.9	partly_thawed
2023-05-27	2	3.58609512	3.3	partly_thawed
2023-05-28	2	4.74635682	4.05	partly_thawed
2023-05-29	2	4.02995337	5.55	partly_thawed
2023-05-30	2	7.52663379	4.8	partly_thawed
2023-05-31	2	19.5718206	4.25	partly_thawed
2023-06-01	2	6.15147443	3.25	partly_thawed
2023-06-02	2	5.0943476	3.7	partly_thawed
2023-06-03	2	12.548897	5.85	partly_thawed
2023-06-04	2	9.62860469	7	partly_thawed
2023-06-06	2	3.89185836	5.9	partly_thawed
2023-06-07	2	9.58988704	6.35	partly_thawed
2023-06-08	2	7.33867681	5.7	partly_thawed
2023-06-09	2	4.58170903	6.6	partly_thawed
2023-06-10	2	15.5404233	6.8	partly_thawed
2023-06-11	2	10.7936538	8.1	partly_thawed
2023-06-12	2	15.3763969	8.7	partly_thawed
2023-06-13	2	1.53925322	8.5	partly_thawed
2023-06-14	2	3.40438595	8.3	partly_thawed
2023-06-15	2	6.48323423	7.4	partly_thawed

2023-06-16	2	14.5803252	8.1	partly_thawed
2023-06-17	2	15.6389211	9.5	partly_thawed
2023-06-18	2	31.8205059	11.25	partly_thawed
2023-06-19	2	44.1913954	11.75	partly_thawed
2023-06-20	2	13.9612921	12.15	partly_thawed
2023-06-21	2	17.662008	13.3	partly_thawed
2023-06-22	2	9.89155847	12.9	partly_thawed
2023-06-23	2	40.8826325	12.5	partly_thawed
2023-06-24	2	79.8489491	10.55	partly_thawed
2023-06-25	2	35.8147969	9.8	partly_thawed
2023-06-26	2	11.7850491	10.4	partly_thawed
2023-06-27	2	13.2740956	10.6	partly_thawed
2023-06-28	2	26.8731422	12.2	partly_thawed
2023-06-29	2	41.6668303	12.75	partly_thawed
2023-06-30	2	14.373135	13.7	partly_thawed
2023-07-01	2	16.4751695	12.8	partly_thawed
2023-07-02	2	22.8080135	12.3	partly_thawed
2023-07-03	2	11.721194	10.7	partly_thawed
2023-07-04	2	57.5855112	9.3	partly_thawed
2023-07-05	2	61.3964171	11.95	partly_thawed
2023-07-06	2	41.2109233	10.7	partly_thawed
2023-07-07	2	19.3064479	11.55	partly_thawed
2023-07-08	2	49.6842127	13.5	partly_thawed
2023-07-09	2	25.3841544	11.9	partly_thawed
2023-07-10	2	80.350965	11.95	partly_thawed
2023-07-11	2	32.5066099	13.5	partly_thawed
2023-07-12	2	19.6550007	13	partly_thawed
2023-07-13	2	23.3160879	12.7	partly_thawed
2023-07-14	2	20.6782469	13	partly_thawed
2023-07-15	2	28.6238958	12.95	partly_thawed
2023-07-16	2	31.3170475	11.1	partly_thawed
2023-07-17	2	69.0423737	10.4	partly_thawed
2023-07-18	2	31.1485143	12.3	partly_thawed
2023-07-19	2	78.4602003	11.05	partly_thawed
2023-07-20	2	110.588726	10.2	partly_thawed
2023-07-21	2	33.5477807	11.2	partly_thawed
2023-07-22	2	21.0885265	10.6	partly_thawed
2023-07-23	2	22.028071	10.4	partly_thawed
2023-07-24	2	35.5289275	10.8	partly_thawed

2023-07-25	2	23.7492942	11.15	partly_thawed
2023-07-26	2	65.9468251	12.3	partly_thawed
2023-07-27	2	128.110722	12.8	partly_thawed
2023-07-28	2	79.8050552	12.5	partly_thawed
2023-07-29	2	56.8759984	13.6	partly_thawed
2023-07-30	2	63.2536861	13.5	partly_thawed
2023-07-31	2	25.0430848	13.2	partly_thawed
2023-08-01	2	26.9955982	13.15	partly_thawed
2023-08-02	2	19.9212208	11.9	partly_thawed
2023-08-03	2	26.5437726	12.3	partly_thawed
2023-08-04	2	34.0101748	12.95	partly_thawed
2023-08-05	2	16.7294357	12.2	partly_thawed
2023-08-06	2	75.4574909	10.4	partly_thawed
2023-08-07	2	31.5647914	10.7	partly_thawed
2023-08-08	2	29.7783092	11.4	partly_thawed
2023-08-09	2	21.8526552	13.2	partly_thawed
2023-08-10	2	68.1945167	13.6	partly_thawed
2023-08-11	2	24.4209532	12.5	partly_thawed
2023-08-12	2	43.2268626	11.85	partly_thawed
2023-08-13	2	53.5576399	11.9	partly_thawed
2023-08-14	2	45.2274227	12.35	partly_thawed
2023-08-15	2	160.839658	13.15	partly_thawed
2023-08-16	2	70.8737833	12.4	partly_thawed
2023-08-17	2	46.837311	12	partly_thawed
2023-08-18	2	57.8732317	11.05	partly_thawed
2023-08-19	2	47.9671115	10.55	partly_thawed
2023-08-20	2	49.4545866	11	partly_thawed
2023-08-21	2	42.9428792	11.9	partly_thawed
2023-08-22	2	131.905466	13	partly_thawed
2023-08-23	2	123.85888	12.95	partly_thawed
2023-08-24	2	41.2154506	12	partly_thawed
2023-08-25	2	68.6044776	11.9	partly_thawed
2023-08-26	2	95.0039126	11	partly_thawed
2023-08-27	2	50.7697585	9.5	partly_thawed
2023-08-28	2	30.4250286	10.8	partly_thawed
2023-08-29	2	47.3675987	11.85	partly_thawed
2023-08-30	2	65.9836321	11.85	partly_thawed
2023-05-19	3	-2.5803204	6.8	intact
2023-05-20	3	1.15638671	7.3	intact

2023-05-22	3	-1.255402	6.7	intaet
2023-05-23	3	2.81969798	8.6	intaet
2023-05-25	3	1.16149635	NA	intaet
2023-05-27	3	0.86285343	6.9	intaet
2023-05-28	3	-0.7032227	NA	intaet
2023-05-29	3	0.4901487	7.1	intaet
2023-05-30	3	0.49772473	6.25	intaet
2023-05-31	3	-2.4676236	5.9	intaet
2023-06-02	3	0.95680016	7.5	intaet
2023-06-07	3	-0.7658941	8.6	intaet
2023-06-10	3	3.43841411	12.4	intaet
2023-06-11	3	-0.2294732	10.1	intaet
2023-06-12	3	-0.6377087	9.3	intaet
2023-06-17	3	2.07956174	12	intaet
2023-06-18	3	-0.6556424	13.55	intaet
2023-06-19	3	8.85655461	15.5	intaet
2023-06-22	3	-1.0366715	14.6	intaet
2023-06-23	3	2.08647798	14.45	intaet
2023-06-25	3	4.67578604	NA	intaet
2023-06-26	3	11.3090816	13.3	intaet
2023-06-27	3	17.8449859	16.1	intaet
2023-06-28	3	-4.1519838	14.6	intaet
2023-06-29	3	1.75473305	14.5	intaet
2023-07-01	3	-0.6927129	13.7	intaet
2023-07-02	3	1.7895277	11.7	intaet
2023-07-04	3	9.72225636	10	intaet
2023-07-05	3	6.35966235	13.9	intaet
2023-07-08	3	10.5210357	13.95	intaet
2023-07-09	3	-1.9971268	13.4	intaet
2023-07-10	3	6.57636546	13	intaet
2023-07-11	3	1.14897533	13.2	intaet
2023-07-13	3	0.73874793	NA	intaet
2023-07-14	3	0.51801415	13.2	intaet
2023-07-16	3	24.1586777	9.9	intaet
2023-07-17	3	-5.6006408	10.7	intaet
2023-07-18	3	-1.4566826	13	intaet
2023-07-20	3	9.4840076	11.1	intaet
2023-07-21	3	-0.0788323	11.8	intaet
2023-07-25	3	2.78941254	NA	intaet

2023-07-27	3	1.47809052	15.45	intact
2023-07-28	3	3.36932495	12.8	intact
2023-07-29	3	-3.8347945	16.9	intact
2023-07-30	3	3.91550813	13.45	intact
2023-08-02	3	1.05771355	13.85	intact
2023-08-04	3	-3.0436606	16.1	intact
2023-08-05	3	-1.9844905	15	intact
2023-08-06	3	1.33543291	12.5	intact
2023-08-07	3	-2.0934105	NA	intact
2023-08-08	3	-1.7480627	NA	intact
2023-08-09	3	4.22978638	15	intact
2023-08-10	3	3.99420254	14.7	intact
2023-08-11	3	2.7661995	13	intact
2023-08-12	3	2.3091427	14.2	intact
2023-08-13	3	43.9516494	11.2	intact
2023-08-14	3	2.99366857	12.5	intact
2023-08-16	3	11.3838865	NA	intact
2023-08-17	3	-1.2168881	11.6	intact
2023-08-19	3	17.0250587	9.9	intact
2023-08-20	3	-2.0284502	13.4	intact
2023-08-21	3	-1.1364975	12.5	intact
2023-08-22	3	8.52438518	13.2	intact
2023-08-24	3	13.7368039	12.9	intact
2023-08-25	3	14.7329223	10	intact
2023-08-26	3	3.78757965	NA	intact
2023-08-27	3	5.75274085	NA	intact
2023-08-28	3	1.54015746	NA	intact
2023-08-29	3	12.2598751	NA	intact
2023-08-30	3	-3.0880699	NA	intact
2023-05-19	4	15.3260797	6.35	partly_thawed
2023-05-20	4	16.3046112	6	partly_thawed
2023-05-21	4	15.2011339	7.2	partly_thawed
2023-05-22	4	18.8625876	5.6	partly_thawed
2023-05-23	4	18.642289	NA	partly_thawed
2023-05-24	4	21.6231619	NA	partly_thawed
2023-05-25	4	19.0604258	4.4	partly_thawed
2023-05-26	4	8.61206747	4.8	partly_thawed
2023-05-27	4	18.7376978	4.95	partly_thawed
2023-05-28	4	18.0772622	5.6	partly_thawed

2023-05-29	4	9.3410204	7.7	partly_thawed
2023-05-30	4	19.9154388	5.3	partly_thawed
2023-05-31	4	20.2870883	4.8	partly_thawed
2023-06-01	4	9.6420955	3.6	partly_thawed
2023-06-02	4	19.5970952	8	partly_thawed
2023-06-03	4	13.967649	6.4	partly_thawed
2023-06-04	4	11.4367081	7.9	partly_thawed
2023-06-05	4	5.52809115	6.1	partly_thawed
2023-06-06	4	7.39703184	8.6	partly_thawed
2023-06-07	4	22.8335209	7.5	partly_thawed
2023-06-08	4	12.5212654	6.95	partly_thawed
2023-06-09	4	8.69966321	11.8	partly_thawed
2023-06-10	4	16.8196508	11.3	partly_thawed
2023-06-11	4	21.3494983	10.9	partly_thawed
2023-06-12	4	19.6490378	11	partly_thawed
2023-06-13	4	3.75432939	12.55	partly_thawed
2023-06-14	4	11.4690303	10.2	partly_thawed
2023-06-15	4	9.8235872	10.9	partly_thawed
2023-06-16	4	19.1560774	13.4	partly_thawed
2023-06-17	4	23.2823381	14.5	partly_thawed
2023-06-18	4	27.1226898	15.5	partly_thawed
2023-06-19	4	23.6041287	16.5	partly_thawed
2023-06-20	4	21.2917605	14	partly_thawed
2023-06-21	4	30.6550238	15.7	partly_thawed
2023-06-22	4	14.1761334	14.7	partly_thawed
2023-06-23	4	29.6107856	15.25	partly_thawed
2023-06-24	4	26.1851638	12.7	partly_thawed
2023-06-25	4	19.1723247	13.35	partly_thawed
2023-06-26	4	22.4637231	12.4	partly_thawed
2023-06-27	4	23.2891672	14.95	partly_thawed
2023-06-28	4	27.026658	14.8	partly_thawed
2023-06-29	4	34.9020762	16.45	partly_thawed
2023-06-30	4	13.4209663	14.4	partly_thawed
2023-07-01	4	22.8990118	13.05	partly_thawed
2023-07-02	4	30.5293099	11.25	partly_thawed
2023-07-03	4	22.4349558	10.2	partly_thawed
2023-07-04	4	38.6929169	13.1	partly_thawed
2023-07-05	4	28.215731	12.1	partly_thawed
2023-07-06	4	35.5901705	13.75	partly_thawed

2023-07-07	4	26.4246888	13.2	partly_thawed
2023-07-08	4	20.2482046	14.7	partly_thawed
2023-07-09	4	35.9015093	15.65	partly_thawed
2023-07-10	4	41.3976089	15.85	partly_thawed
2023-07-11	4	41.5938532	15	partly_thawed
2023-07-12	4	26.1006239	13.5	partly_thawed
2023-07-13	4	31.041448	13.7	partly_thawed
2023-07-14	4	40.3052808	13.3	partly_thawed
2023-07-15	4	32.1065483	14.1	partly_thawed
2023-07-16	4	28.8956505	11.45	partly_thawed
2023-07-17	4	48.3482861	13.3	partly_thawed
2023-07-18	4	41.0063463	13.45	partly_thawed
2023-07-19	4	43.5113186	12	partly_thawed
2023-07-20	4	58.1198302	12.35	partly_thawed
2023-07-21	4	44.4942575	12.75	partly_thawed
2023-07-22	4	37.1977352	12	partly_thawed
2023-07-23	4	36.2617427	12.15	partly_thawed
2023-07-24	4	36.6393035	12.75	partly_thawed
2023-07-25	4	35.4331152	13.75	partly_thawed
2023-07-26	4	41.8456117	15	partly_thawed
2023-07-27	4	49.2020487	15.85	partly_thawed
2023-07-28	4	55.169586	16	partly_thawed
2023-07-29	4	46.2299463	15.05	partly_thawed
2023-07-30	4	51.4052057	13.95	partly_thawed
2023-07-31	4	38.8404046	13.85	partly_thawed
2023-08-01	4	43.0606422	14.4	partly_thawed
2023-08-02	4	44.7060991	13.95	partly_thawed
2023-08-03	4	34.382709	14.6	partly_thawed
2023-08-04	4	43.6758417	14.65	partly_thawed
2023-08-05	4	30.6957938	13.8	partly_thawed
2023-08-06	4	59.0955896	13.55	partly_thawed
2023-08-07	4	48.3871803	12.3	partly_thawed
2023-08-08	4	51.7724684	15	partly_thawed
2023-08-09	4	38.4434676	15.55	partly_thawed
2023-08-10	4	74.9909469	14.35	partly_thawed
2023-08-11	4	55.5844904	13.9	partly_thawed
2023-08-12	4	66.6026489	13.9	partly_thawed
2023-08-13	4	58.589253	13.6	partly_thawed
2023-08-14	4	83.0673361	13.95	partly_thawed

2023-08-15	4	89.1140624	15.35	partly_thawed
2023-08-16	4	87.0601228	13.3	partly_thawed
2023-08-17	4	67.5630045	13.55	partly_thawed
2023-08-18	4	80.3882045	12.3	partly_thawed
2023-08-19	4	72.6660605	12.8	partly_thawed
2023-08-20	4	47.6804448	13.5	partly_thawed
2023-08-21	4	69.7409064	14.35	partly_thawed
2023-08-22	4	103.851364	14.75	partly_thawed
2023-08-23	4	100.810651	14.55	partly_thawed
2023-08-24	4	98.2969009	13.95	partly_thawed
2023-08-25	4	77.4292843	13	partly_thawed
2023-08-26	4	71.6129038	13.05	partly_thawed
2023-08-27	4	87.5944317	13.3	partly_thawed
2023-08-28	4	61.3708353	11.8	partly_thawed
2023-08-29	4	96.4069224	13	partly_thawed
2023-08-30	4	109.6439	13.7	partly_thawed
2023-05-25	5	1.46122778	4.85	intaet
2023-05-26	5	0.6737177	2.5	intaet
2023-05-29	5	0.54930674	4.4	intaet
2023-05-30	5	2.60528065	5.2	intaet
2023-05-31	5	-1.4114502	3	intaet
2023-06-01	5	4.15535495	2.3	intaet
2023-06-09	5	20.0151705	5.35	intaet
2023-06-10	5	8.1201162	3.8	intaet
2023-06-11	5	-0.4248935	10.1	intaet
2023-06-12	5	3.14745001	6.8	intaet
2023-06-13	5	0.593267	7.4	intaet
2023-06-20	5	-2.0807684	13.9	intaet
2023-06-21	5	27.2457403	14.9	intaet
2023-06-22	5	32.2566005	15.3	intaet
2023-06-23	5	60.9184426	14.8	intaet
2023-06-24	5	11.4244715	11.95	intaet
2023-06-26	5	33.3394485	11.3	intaet
2023-06-27	5	24.0565414	13.3	intaet
2023-06-29	5	57.0662104	12.8	intaet
2023-06-30	5	35.8270265	14.7	intaet
2023-07-01	5	119.791475	14.85	intaet
2023-07-02	5	89.6080711	13.25	intaet
2023-07-03	5	57.8293841	12	intaet

2023-07-04	5	40.1150495	12.4	intaet
2023-07-05	5	35.7539116	11.85	intaet
2023-07-06	5	22.465272	13.15	intaet
2023-07-07	5	30.4546503	15.9	intaet
2023-07-08	5	10.4237423	13.1	intaet
2023-07-09	5	5.68477271	11.5	intaet
2023-07-10	5	60.0125744	11.35	intaet
2023-07-11	5	39.538247	15.9	intaet
2023-07-12	5	14.1616398	13.7	intaet
2023-07-13	5	49.5157043	14.05	intaet
2023-07-14	5	37.5150978	15.4	intaet
2023-07-15	5	25.6094225	11.7	intaet
2023-07-16	5	33.9046124	9.6	intaet
2023-07-17	5	29.4406576	13	intaet
2023-07-20	5	79.9097731	12.3	intaet
2023-07-21	5	56.6512727	12.2	intaet
2023-07-22	5	70.3010276	12.6	intaet
2023-07-24	5	61.2907393	12.7	intaet
2023-07-25	5	58.2712421	12.6	intaet
2023-07-26	5	56.4967571	12.35	intaet
2023-07-27	5	50.2199107	13.3	intaet
2023-07-28	5	62.2479228	13.55	intaet
2023-07-29	5	52.9781105	14.1	intaet
2023-08-01	5	88.4730115	14.1	intaet
2023-08-02	5	39.9236586	12.9	intaet
2023-08-04	5	75.8082139	14.5	intaet
2023-08-05	5	81.302771	11.4	intaet
2023-08-06	5	81.8067879	9.9	intaet
2023-08-07	5	80.1733121	12.5	intaet
2023-08-08	5	127.154145	16	intaet
2023-08-09	5	47.2237119	15.5	intaet
2023-08-10	5	123.58489	13.9	intaet
2023-08-11	5	89.7526167	13.2	intaet
2023-08-12	5	91.5041605	14.9	intaet
2023-08-13	5	80.9764569	11.5	intaet
2023-08-14	5	95.7200264	14.55	intaet
2023-08-15	5	70.2118506	13.35	intaet
2023-08-16	5	81.7665149	11.6	intaet
2023-08-17	5	11.3585358	11.8	intaet

2023-08-18	5	33.9012364	11.85	intact
2023-08-19	5	59.6545486	11.5	intact
2023-08-20	5	70.2551536	10.9	intact
2023-08-21	5	66.8491835	13.65	intact
2023-08-22	5	65.2073029	13.7	intact
2023-08-23	5	86.9935888	14.1	intact
2023-08-24	5	73.8134836	12.9	intact
2023-08-25	5	80.2930753	10.6	intact
2023-08-26	5	71.1902386	11.6	intact
2023-08-27	5	44.9537462	12.4	intact
2023-08-28	5	50.1999253	11.5	intact
2023-08-29	5	52.3861745	12.7	intact
2023-08-30	5	106.122498	11.9	intact
2023-05-19	6	8.3630998	3.1	partly_thawed
2023-05-20	6	11.6693504	3.1	partly_thawed
2023-05-21	6	18.0408983	3.95	partly_thawed
2023-05-22	6	22.6504773	4.2	partly_thawed
2023-05-23	6	19.8541094	4.4	partly_thawed
2023-05-24	6	14.2022763	3.7	partly_thawed
2023-05-25	6	18.2098957	3.6	partly_thawed
2023-05-26	6	14.6898552	3.05	partly_thawed
2023-05-27	6	13.337191	3.2	partly_thawed
2023-05-28	6	17.0115001	4.4	partly_thawed
2023-05-29	6	17.7840109	4.15	partly_thawed
2023-05-30	6	20.0638626	3.9	partly_thawed
2023-05-31	6	22.4345768	3.9	partly_thawed
2023-06-01	6	20.6394943	3.1	partly_thawed
2023-06-02	6	21.4132642	4.45	partly_thawed
2023-06-03	6	23.4969754	5.4	partly_thawed
2023-06-04	6	18.4901259	5	partly_thawed
2023-06-05	6	12.4229704	4.85	partly_thawed
2023-06-06	6	16.9432259	5.6	partly_thawed
2023-06-07	6	23.442394	6.2	partly_thawed
2023-06-08	6	19.689198	5.65	partly_thawed
2023-06-09	6	30.7806593	6.75	partly_thawed
2023-06-10	6	29.6977711	6.65	partly_thawed
2023-06-11	6	19.6793493	7.05	partly_thawed
2023-06-12	6	16.8144302	7.8	partly_thawed
2023-06-13	6	12.5208428	7.4	partly_thawed

2023-06-14	6	20.2614767	7.7	partly_thawed
2023-06-15	6	22.5828409	7.3	partly_thawed
2023-06-16	6	38.2572792	7.7	partly_thawed
2023-06-17	6	39.1763921	8.7	partly_thawed
2023-06-18	6	39.1541315	10.2	partly_thawed
2023-06-19	6	40.0347046	11.1	partly_thawed
2023-06-20	6	25.1664938	11.05	partly_thawed
2023-06-21	6	39.1694686	12.5	partly_thawed
2023-06-22	6	13.3026781	11.45	partly_thawed
2023-06-23	6	43.5449617	13.45	partly_thawed
2023-06-24	6	40.9599485	11.45	partly_thawed
2023-06-25	6	33.7630086	11.3	partly_thawed
2023-06-26	6	14.108924	10.3	partly_thawed
2023-06-27	6	29.1704193	11.3	partly_thawed
2023-06-28	6	34.0001316	11.7	partly_thawed
2023-06-29	6	57.9189061	12.3	partly_thawed
2023-06-30	6	21.4170225	12	partly_thawed
2023-07-01	6	19.7927166	11.55	partly_thawed
2023-07-02	6	33.649174	11.2	partly_thawed
2023-07-03	6	22.3059869	9.8	partly_thawed
2023-07-04	6	77.5904311	9.4	partly_thawed
2023-07-05	6	42.6626879	10.55	partly_thawed
2023-07-06	6	43.1515249	10.15	partly_thawed
2023-07-07	6	48.6732313	10.8	partly_thawed
2023-07-08	6	39.6743724	12.35	partly_thawed
2023-07-09	6	48.1502657	11.45	partly_thawed
2023-07-10	6	85.2151002	11.6	partly_thawed
2023-07-11	6	73.426825	12.6	partly_thawed
2023-07-12	6	28.3342259	11.7	partly_thawed
2023-07-13	6	24.0755872	11.7	partly_thawed
2023-07-14	6	19.4538447	12	partly_thawed
2023-07-15	6	48.9913041	12.25	partly_thawed
2023-07-16	6	20.5889678	10.3	partly_thawed
2023-07-17	6	68.5586901	10.7	partly_thawed
2023-07-18	6	50.322429	11.95	partly_thawed
2023-07-19	6	49.8566426	10.9	partly_thawed
2023-07-20	6	58.7793876	10.3	partly_thawed
2023-07-21	6	35.0609548	11.3	partly_thawed
2023-07-22	6	26.8719461	11	partly_thawed

2023-07-23	6	29.127419	10.55	partly_thawed
2023-07-24	6	32.3729623	10.9	partly_thawed
2023-07-25	6	32.8231256	11.3	partly_thawed
2023-07-26	6	50.4473485	11.95	partly_thawed
2023-07-27	6	110.332247	12.55	partly_thawed
2023-07-28	6	92.7295683	12.75	partly_thawed
2023-07-29	6	60.3420529	13.45	partly_thawed
2023-07-30	6	53.361103	12.7	partly_thawed
2023-07-31	6	29.3270414	12.25	partly_thawed
2023-08-01	6	36.8111944	11.9	partly_thawed
2023-08-02	6	48.9128661	12.75	partly_thawed
2023-08-03	6	24.4034451	12.9	partly_thawed
2023-08-04	6	50.6965068	14.1	partly_thawed
2023-08-05	6	59.7348555	13.05	partly_thawed
2023-08-06	6	101.669452	11.3	partly_thawed
2023-08-07	6	46.415161	12	partly_thawed
2023-08-08	6	50.7337198	12.15	partly_thawed
2023-08-09	6	50.8757148	14.2	partly_thawed
2023-08-10	6	107.105636	14.2	partly_thawed
2023-08-11	6	57.6274551	13.3	partly_thawed
2023-08-12	6	68.3311498	12.55	partly_thawed
2023-08-13	6	50.7633661	12.6	partly_thawed
2023-08-14	6	105.827707	13.2	partly_thawed
2023-08-15	6	104.659029	13.9	partly_thawed
2023-08-16	6	90.186093	13.2	partly_thawed
2023-08-17	6	47.7516914	13.1	partly_thawed
2023-08-18	6	68.4988103	12.25	partly_thawed
2023-08-19	6	83.7797336	11.95	partly_thawed
2023-08-20	6	65.4200639	11.7	partly_thawed
2023-08-21	6	86.6755397	12.9	partly_thawed
2023-08-22	6	101.218752	13.6	partly_thawed
2023-08-23	6	105.18271	13.7	partly_thawed
2023-08-24	6	110.510497	12.8	partly_thawed
2023-08-25	6	101.360275	12.25	partly_thawed
2023-08-26	6	110.248594	11.4	partly_thawed
2023-08-27	6	74.1478638	11.9	partly_thawed
2023-08-28	6	63.0693781	11.9	partly_thawed
2023-08-29	6	97.0584329	12.35	partly_thawed
2023-08-30	6	116.592803	13	partly_thawed

2023-05-19	7	49.334863	2.05	fully_thawed
2023-05-20	7	46.9200393	2.05	fully_thawed
2023-05-21	7	52.0751732	2.3	fully_thawed
2023-05-22	7	75.3469779	2.35	fully_thawed
2023-05-23	7	44.6685192	3	fully_thawed
2023-05-24	7	33.8936121	2.9	fully_thawed
2023-05-25	7	37.6489882	2.65	fully_thawed
2023-05-26	7	34.7523409	2.6	fully_thawed
2023-05-27	7	39.9671258	2.6	fully_thawed
2023-05-28	7	39.3415505	3.65	fully_thawed
2023-05-29	7	34.1545325	3.25	fully_thawed
2023-05-30	7	36.1480781	3.15	fully_thawed
2023-05-31	7	31.5812416	3.25	fully_thawed
2023-06-01	7	34.2491326	2.75	fully_thawed
2023-06-02	7	36.3974991	3.65	fully_thawed
2023-06-03	7	36.4606779	4	fully_thawed
2023-06-04	7	33.4537363	4.05	fully_thawed
2023-06-05	7	30.5260161	4	fully_thawed
2023-06-06	7	39.7875148	4.35	fully_thawed
2023-06-07	7	44.0400964	4.4	fully_thawed
2023-06-08	7	39.0480798	4.3	fully_thawed
2023-06-09	7	50.2600447	4.5	fully_thawed
2023-06-10	7	72.8707437	4.4	fully_thawed
2023-06-11	7	54.8621741	5.3	fully_thawed
2023-06-12	7	46.3315212	5.85	fully_thawed
2023-06-13	7	46.4795599	5.7	fully_thawed
2023-06-14	7	49.2634297	5.75	fully_thawed
2023-06-15	7	52.4206463	5.8	fully_thawed
2023-06-16	7	74.340552	5.15	fully_thawed
2023-06-17	7	80.1579366	4.9	fully_thawed
2023-06-18	7	92.6844436	5.8	fully_thawed
2023-06-19	7	112.902023	6.45	fully_thawed
2023-06-20	7	76.8289006	7.1	fully_thawed
2023-06-21	7	103.716188	9.15	fully_thawed
2023-06-22	7	64.6615473	7.75	fully_thawed
2023-06-23	7	104.424053	8.5	fully_thawed
2023-06-24	7	91.6352675	7.5	fully_thawed
2023-06-25	7	108.874606	7.15	fully_thawed
2023-06-26	7	78.4405403	6.4	fully_thawed

2023-06-27	7	97.4924365	7.45	fully_thawed
2023-06-28	7	138.313482	7.35	fully_thawed
2023-06-29	7	150.786801	6.75	fully_thawed
2023-06-30	7	82.7247754	7.15	fully_thawed
2023-07-01	7	93.5174097	6.65	fully_thawed
2023-07-02	7	84.1199896	6.65	fully_thawed
2023-07-03	7	68.8906932	5.35	fully_thawed
2023-07-04	7	125.311515	4.65	fully_thawed
2023-07-05	7	82.7811367	6.6	fully_thawed
2023-07-06	7	115.519992	5.8	fully_thawed
2023-07-07	7	83.6127463	6.15	fully_thawed
2023-07-08	7	117.799471	7.45	fully_thawed
2023-07-09	7	127.258105	7.15	fully_thawed
2023-07-10	7	134.356642	5.05	fully_thawed
2023-07-11	7	119.822284	6.3	fully_thawed
2023-07-12	7	63.2641997	6.6	fully_thawed
2023-07-13	7	73.3970921	6.95	fully_thawed
2023-07-14	7	64.4319988	7.35	fully_thawed
2023-07-15	7	87.7517355	8.2	fully_thawed
2023-07-16	7	60.0648654	6.65	fully_thawed
2023-07-17	7	86.8304636	6.3	fully_thawed
2023-07-18	7	89.9447192	7.4	fully_thawed
2023-07-19	7	104.248884	7.1	fully_thawed
2023-07-20	7	96.1184814	7.2	fully_thawed
2023-07-21	7	72.9758352	8.2	fully_thawed
2023-07-22	7	50.8879982	8.25	fully_thawed
2023-07-23	7	47.890464	7.85	fully_thawed
2023-07-24	7	67.628543	8.05	fully_thawed
2023-07-25	7	66.104418	8.3	fully_thawed
2023-07-26	7	59.0960214	8.85	fully_thawed
2023-07-27	7	107.272419	8.55	fully_thawed
2023-07-28	7	125.58199	9.45	fully_thawed
2023-07-29	7	105.040756	10.35	fully_thawed
2023-07-30	7	71.9771293	9.4	fully_thawed
2023-07-31	7	49.8456284	10	fully_thawed
2023-08-01	7	67.1301054	10.3	fully_thawed
2023-08-02	7	68.0543255	9.55	fully_thawed
2023-08-03	7	53.418273	10.25	fully_thawed
2023-08-04	7	87.755188	12	fully_thawed

2023-08-05	7	107.694219	11.25	fully_thawed
2023-08-06	7	142.426043	9.6	fully_thawed
2023-08-07	7	59.0778337	10.3	fully_thawed
2023-08-08	7	70.8195516	11.5	fully_thawed
2023-08-09	7	61.1767954	13.2	fully_thawed
2023-08-10	7	122.236264	13.4	fully_thawed
2023-08-11	7	76.1331003	12.6	fully_thawed
2023-08-12	7	86.5827151	12.55	fully_thawed
2023-08-13	7	87.0160802	11.85	fully_thawed
2023-08-14	7	134.443476	12.7	fully_thawed
2023-08-15	7	177.273142	13.35	fully_thawed
2023-08-16	7	123.484146	12.3	fully_thawed
2023-08-17	7	131.386761	12.1	fully_thawed
2023-08-18	7	171.532134	11.05	fully_thawed
2023-08-19	7	103.586558	10.75	fully_thawed
2023-08-20	7	76.0763399	11.15	fully_thawed
2023-08-21	7	89.1069265	12.2	fully_thawed
2023-08-22	7	147.526551	12.65	fully_thawed
2023-08-23	7	182.018833	12.9	fully_thawed
2023-08-24	7	242.91605	11.9	fully_thawed
2023-08-25	7	112.696976	11	fully_thawed
2023-08-26	7	204.616261	10.2	fully_thawed
2023-08-27	7	88.5555957	10.1	fully_thawed
2023-08-28	7	69.6624609	10.95	fully_thawed
2023-08-29	7	83.0563735	11.75	fully_thawed
2023-08-30	7	198.675869	11.95	fully_thawed
2023-05-19	8	34.7006239	9.4	fully_thawed
2023-05-20	8	20.7060914	11.2	fully_thawed
2023-05-21	8	39.7632249	10.7	fully_thawed
2023-05-22	8	51.4766506	12.9	fully_thawed
2023-05-23	8	39.2495605	9.95	fully_thawed
2023-05-24	8	33.4763883	8.9	fully_thawed
2023-05-25	8	21.6617507	7.9	fully_thawed
2023-05-26	8	31.3390259	4.5	fully_thawed
2023-05-27	8	32.3995898	6.85	fully_thawed
2023-05-28	8	19.3751497	7.65	fully_thawed
2023-05-29	8	20.5861088	7.35	fully_thawed
2023-05-30	8	37.5520532	6.75	fully_thawed
2023-05-31	8	23.703279	4.75	fully_thawed

2023-06-01	8	24.8348066	6	fully_thawed
2023-06-02	8	36.1691973	7.35	fully_thawed
2023-06-03	8	35.2229112	7.9	fully_thawed
2023-06-04	8	34.5912683	8.05	fully_thawed
2023-06-05	8	23.7471868	7.1	fully_thawed
2023-06-06	8	34.8645607	9	fully_thawed
2023-06-07	8	51.7544084	10.15	fully_thawed
2023-06-08	8	30.2154105	9	fully_thawed
2023-06-09	8	55.8270964	9.85	fully_thawed
2023-06-10	8	58.3342632	12.4	fully_thawed
2023-06-11	8	63.8823588	13.5	fully_thawed
2023-06-12	8	58.3933537	13.25	fully_thawed
2023-06-13	8	42.5780141	11.7	fully_thawed
2023-06-14	8	38.3218216	11.3	fully_thawed
2023-06-15	8	42.1898655	12.3	fully_thawed
2023-06-16	8	91.4366961	16	fully_thawed
2023-06-17	8	97.7764602	15.85	fully_thawed
2023-06-18	8	115.451319	18.45	fully_thawed
2023-06-19	8	104.867502	18.55	fully_thawed
2023-06-20	8	93.700883	17.95	fully_thawed
2023-06-21	8	86.0736841	18.05	fully_thawed
2023-06-22	8	64.7044161	17.9	fully_thawed
2023-06-23	8	121.630873	15.35	fully_thawed
2023-06-24	8	123.917059	11.9	fully_thawed
2023-06-25	8	114.339939	15.8	fully_thawed
2023-06-26	8	82.7727499	15.2	fully_thawed
2023-06-27	8	100.223707	16.65	fully_thawed
2023-06-28	8	111.760012	18.2	fully_thawed
2023-06-29	8	125.297228	20.15	fully_thawed
2023-06-30	8	85.4755693	16.45	fully_thawed
2023-07-01	8	74.3489467	14.85	fully_thawed
2023-07-02	8	103.054436	8.95	fully_thawed
2023-07-03	8	83.7350237	10.5	fully_thawed
2023-07-04	8	124.946855	17.05	fully_thawed
2023-07-05	8	89.2157471	12.4	fully_thawed
2023-07-06	8	101.540381	16.95	fully_thawed
2023-07-07	8	90.7057301	18.65	fully_thawed
2023-07-08	8	82.0840488	14.55	fully_thawed
2023-07-09	8	99.1335258	17	fully_thawed

2023-07-10	8	103.139045	19.3	fully_thawed
2023-07-11	8	91.7801651	22.8	fully_thawed
2023-07-12	8	43.576118	15.9	fully_thawed
2023-07-13	8	60.9340832	14.95	fully_thawed
2023-07-14	8	60.0526603	13.7	fully_thawed
2023-07-15	8	76.4054909	15	fully_thawed
2023-07-16	8	45.7691207	13.25	fully_thawed
2023-07-17	8	88.0293306	15.75	fully_thawed
2023-07-18	8	79.4695261	14.5	fully_thawed
2023-07-19	8	72.7707008	11.7	fully_thawed
2023-07-20	8	100.605945	13.7	fully_thawed
2023-07-21	8	54.6632769	13.2	fully_thawed
2023-07-22	8	49.1530095	12.85	fully_thawed
2023-07-23	8	52.0787468	12.45	fully_thawed
2023-07-24	8	55.5108827	13.2	fully_thawed
2023-07-25	8	55.0531341	14.75	fully_thawed
2023-07-26	8	80.6270529	14.8	fully_thawed
2023-07-27	8	179.422789	17	fully_thawed
2023-07-28	8	135.095657	18.4	fully_thawed
2023-07-29	8	121.325816	16.25	fully_thawed
2023-07-30	8	112.376703	15.35	fully_thawed
2023-07-31	8	65.010212	16.8	fully_thawed
2023-08-01	8	98.6857163	15.35	fully_thawed
2023-08-02	8	98.081123	15.55	fully_thawed
2023-08-03	8	55.3702881	15.25	fully_thawed
2023-08-04	8	118.522215	16.7	fully_thawed
2023-08-05	8	138.729082	12.55	fully_thawed
2023-08-06	8	190.065485	15.6	fully_thawed
2023-08-07	8	64.4686313	14.7	fully_thawed
2023-08-08	8	72.2752781	17.45	fully_thawed
2023-08-09	8	78.5584928	17.3	fully_thawed
2023-08-10	8	158.331138	14.8	fully_thawed
2023-08-11	8	79.5334828	14.4	fully_thawed
2023-08-12	8	96.4098046	13.55	fully_thawed
2023-08-13	8	74.9828709	13.95	fully_thawed
2023-08-14	8	140.817714	14.8	fully_thawed
2023-08-15	8	249.731429	16.1	fully_thawed
2023-08-16	8	151.419455	12.8	fully_thawed
2023-08-17	8	151.557401	12.35	fully_thawed

2023-08-18	8	163.595921	14	fully_thawed
2023-08-19	8	80.9519732	12.15	fully_thawed
2023-08-20	8	62.6858435	13.65	fully_thawed
2023-08-21	8	71.1987865	14.6	fully_thawed
2023-08-22	8	197.024031	14.7	fully_thawed
2023-08-23	8	225.034049	14.75	fully_thawed
2023-08-24	8	154.545038	15.05	fully_thawed
2023-08-25	8	100.121819	13.5	fully_thawed
2023-08-26	8	142.596869	15.45	fully_thawed
2023-08-27	8	68.0651359	12.9	fully_thawed
2023-08-28	8	61.5780643	13.3	fully_thawed
2023-08-29	8	89.8932177	12.75	fully_thawed
2023-08-30	8	194.667128	14.35	fully_thawed
2023-05-19	9	21.8601571	1.3	fully_thawed
2023-05-20	9	15.2725512	1.35	fully_thawed
2023-05-21	9	23.3541124	1.3	fully_thawed
2023-05-22	9	46.1883437	1.2	fully_thawed
2023-05-23	9	28.4648803	1.6	fully_thawed
2023-05-24	9	20.6993939	1.65	fully_thawed
2023-05-25	9	23.3251575	1.6	fully_thawed
2023-05-26	9	25.8304637	1.7	fully_thawed
2023-05-27	9	29.0562812	1.7	fully_thawed
2023-05-28	9	28.4121618	1.8	fully_thawed
2023-05-29	9	21.9174638	1.7	fully_thawed
2023-05-30	9	30.1660976	2	fully_thawed
2023-05-31	9	18.2088374	1.85	fully_thawed
2023-06-01	9	28.7907459	1.95	fully_thawed
2023-06-02	9	31.9483831	2.2	fully_thawed
2023-06-03	9	15.9631516	2.9	fully_thawed
2023-06-04	9	17.8134991	3.2	fully_thawed
2023-06-05	9	17.2227231	2.7	fully_thawed
2023-06-06	9	27.7192954	3.3	fully_thawed
2023-06-07	9	30.9188492	3.4	fully_thawed
2023-06-08	9	16.9136484	3.1	fully_thawed
2023-06-09	9	32.4575906	3.6	fully_thawed
2023-06-10	9	30.0779752	3.1	fully_thawed
2023-06-11	9	43.2075311	3.1	fully_thawed
2023-06-12	9	18.1121587	3.4	fully_thawed
2023-06-13	9	11.5920986	3.3	fully_thawed

2023-06-14	9	20.0512105	3.1	fully_thawed
2023-06-15	9	28.7655978	2.8	fully_thawed
2023-06-16	9	42.6659009	1.6	fully_thawed
2023-06-17	9	43.4093611	0.9	fully_thawed
2023-06-18	9	34.4648482	1.1	fully_thawed
2023-06-19	9	53.9728336	1.2	fully_thawed
2023-06-20	9	35.0823231	1.1	fully_thawed
2023-06-21	9	44.3443703	3.45	fully_thawed
2023-06-22	9	40.5118492	1.15	fully_thawed
2023-06-23	9	66.3432432	4.15	fully_thawed
2023-06-24	9	71.9940645	3.95	fully_thawed
2023-06-25	9	66.9624634	4.3	fully_thawed
2023-06-26	9	37.829216	2.7	fully_thawed
2023-06-27	9	43.2616535	3.3	fully_thawed
2023-06-28	9	35.4868038	3.15	fully_thawed
2023-06-29	9	56.0230485	2.5	fully_thawed
2023-06-30	9	36.3826788	3.1	fully_thawed
2023-07-01	9	36.7027491	2.6	fully_thawed
2023-07-02	9	62.9398655	4.05	fully_thawed
2023-07-03	9	34.0261777	3.7	fully_thawed
2023-07-04	9	106.305431	2.1	fully_thawed
2023-07-05	9	69.6056053	4.6	fully_thawed
2023-07-06	9	55.6372893	3.6	fully_thawed
2023-07-07	9	54.1536993	2.05	fully_thawed
2023-07-08	9	56.7964652	4.7	fully_thawed
2023-07-09	9	84.4408589	3.75	fully_thawed
2023-07-10	9	138.094439	2.6	fully_thawed
2023-07-11	9	90.4711308	3.1	fully_thawed
2023-07-12	9	49.3281588	3.7	fully_thawed
2023-07-13	9	67.5695327	4.2	fully_thawed
2023-07-14	9	64.166318	5.5	fully_thawed
2023-07-15	9	92.4036704	6.8	fully_thawed
2023-07-16	9	61.672136	6.2	fully_thawed
2023-07-17	9	118.601218	5.9	fully_thawed
2023-07-18	9	86.5749823	7.9	fully_thawed
2023-07-19	9	110.341088	8	fully_thawed
2023-07-20	9	94.3315022	7.7	fully_thawed
2023-07-21	9	77.8990507	8.75	fully_thawed
2023-07-22	9	76.7521751	8.85	fully_thawed

2023-07-23	9	65.2453703	8.6	fully_thawed
2023-07-24	9	80.0353096	9.3	fully_thawed
2023-07-25	9	62.3878736	9.7	fully_thawed
2023-07-26	9	97.3968974	9.15	fully_thawed
2023-07-27	9	191.698098	9.7	fully_thawed
2023-07-28	9	193.206865	10.7	fully_thawed
2023-07-29	9	92.986422	11.3	fully_thawed
2023-07-30	9	117.88812	11.5	fully_thawed
2023-07-31	9	83.9161709	10.45	fully_thawed
2023-08-01	9	82.0950356	11.6	fully_thawed
2023-08-02	9	136.809756	11.6	fully_thawed
2023-08-03	9	96.5049759	11.7	fully_thawed
2023-08-04	9	113.08585	13.1	fully_thawed
2023-08-05	9	102.427354	12.75	fully_thawed
2023-08-06	9	299.392644	12.3	fully_thawed
2023-08-07	9	94.2441887	12.15	fully_thawed
2023-08-08	9	88.0675217	10.9	fully_thawed
2023-08-09	9	104.1454	13.1	fully_thawed
2023-08-10	9	202.513157	13.4	fully_thawed
2023-08-11	9	109.054042	13.1	fully_thawed
2023-08-12	9	100.641251	12.7	fully_thawed
2023-08-13	9	90.3502941	12.9	fully_thawed
2023-08-14	9	113.301802	12.65	fully_thawed
2023-08-15	9	270.537667	12.6	fully_thawed
2023-08-16	9	233.716298	12.65	fully_thawed
2023-08-17	9	153.002257	12.3	fully_thawed
2023-08-18	9	165.807156	12.1	fully_thawed
2023-08-19	9	269.796425	11.5	fully_thawed
2023-08-20	9	115.506318	11.55	fully_thawed
2023-08-21	9	200.724416	11.9	fully_thawed
2023-08-22	9	285.042443	12.5	fully_thawed
2023-08-23	9	263.455436	12.65	fully_thawed
2023-08-24	9	146.866361	12	fully_thawed
2023-08-25	9	135.188755	10.9	fully_thawed
2023-08-26	9	302.047003	11.45	fully_thawed
2023-08-27	9	160.286048	11	fully_thawed
2023-08-28	9	95.1710018	11.15	fully_thawed
2023-08-29	9	164.601244	11.2	fully_thawed
2023-08-30	9	375.879582	11.7	fully_thawed

2023-07-08	8	82.0840488	84.6694723	15.85	fully thawed
2023-07-09	8	99.1335258	94.3421708	20.1125	fully thawed
2023-07-10	8	103.139045	116.06328	19.025	fully thawed
2023-07-11	8	91.7801651	85.9948847	20.175	fully thawed
2023-07-12	8	42.8239454	53.3858829	20.35	fully thawed
2023-07-13	8	60.9340832	73.6003756	16.7625	fully thawed
2023-07-14	8	60.0526603	66.8935262	14.575	fully thawed
2023-07-15	8	76.4054909	83.9482106	14.4625	fully thawed
2023-07-16	8	45.7691207	46.8267716	13.4125	fully thawed
2023-07-17	8	88.0293306	85.3056854	15.3375	fully thawed
2023-07-18	8	79.4695261	73.9802775	16.05	fully thawed
2023-07-19	8	72.7707008	98.8396103	12.5875	fully thawed
2023-07-20	8	100.605945	97.1037608	13.6625	fully thawed
2023-07-21	8	54.6632769	58.9828956	13.4125	fully thawed
2023-07-22	8	49.1530095	50.0321278	13.55	fully thawed
2023-07-23	8	52.0787468	52.0586663	14.4375	fully thawed
2023-07-24	8	55.5108827	77.0189918	15.2375	fully thawed
2023-07-25	8	55.0531341	75.2777923	15.3125	fully thawed
2023-07-26	8	80.6270529	90.3159352	16.7	fully thawed
2023-07-27	8	179.422789	177.185227	20.025	fully thawed
2023-07-28	8	135.095657	136.476995	20.175	fully thawed
2023-07-29	8	121.325816	140.213709	19.425	fully thawed
2023-07-30	8	112.376703	123.029358	16.4625	fully thawed
2023-07-31	8	65.010212	62.6815346	17.85	fully thawed
2023-08-01	8	98.6857163	93.9872872	15.55	fully thawed
2023-08-02	8	98.081123	88.0297787	15.125	fully thawed
2023-08-03	8	55.3702881	63.9778193	17.075	fully thawed
2023-08-04	8	114.624674	116.300391	16.5125	fully thawed
2023-08-05	8	138.729082	138.288381	14.4375	fully thawed
2023-08-06	8	194.554335	193.395251	14.275	fully thawed
2023-08-07	8	68.9633448	81.0578537	14.075	fully thawed
2023-08-08	8	72.2752781	79.3467784	17.675	fully thawed
2023-08-09	8	73.333636	129.937336	18.3625	fully thawed
2023-08-10	8	158.331138	159.917908	14	fully thawed
2023-08-11	8	73.1789191	78.7288633	14.1875	fully thawed
2023-08-12	8	96.4098046	124.391776	13.925	fully thawed
2023-08-13	8	74.9828709	135.380888	13.5875	fully thawed
2023-08-14	8	140.817714	150.033294	15.4625	fully thawed
2023-08-15	8	249.731429	236.124016	16.4	fully thawed

2023-08-29	9	164.601244	235.245973	11.4125	fully thawed
2023-08-30	9	375.879582	372.361953	11.6375	fully thawed

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865 Table C5: Results of generalized additive models (GAM) used for determining CH₄ flux season values. Note: Intact [23](#) plot GAM R²_{adj}<0.1, and the CH₄ flux periods are based on moving 7-day medians. CI = 95% confidence interval.

Chamber	R ² _{adj}	p-value	CH ₄ flux period	CH ₄ flux period value (mg CH ₄ m ⁻² d ⁻¹)	95% CI	CH ₄ flux period date (YYYY-MM-DD)
Intact 1	0.320.1 9	<0.001	Early	-0.10.135	-0.6-0.43 0.30.74	2023-05-192023-08-01
			Middle	0.42.029	0.20.91 - 0.64	2023-08-162023-08-21
			Peak	1.24.297	0.71.45 - 1.911.78	2023-08-302023-08-20
Intact 2	-	-	Early	0.3-0.05	-	2023-05-192023-05-20
			Middle	0.48.041	-	2023-07-062023-07-05
			Peak	1.011.384	-	2023-08-152023-08-16
Intact 3	0.850.6 3	<0.001	Early	5.87.717	3.84.89 - 8.912.14	2023-06-252023-06-18
			Middle	29.936.032	19.6.24.8 - 45.452.35	2023-07-262023-07-10
			Peak	56.869.088	36.747.49 - 88.1100.5	2023-08-252023-08-11
Partly thawed 1	0.760.6 2	<0.001	Early	9.811.335	7.99.18 - 12.013	2023-06-162023-06-12
			Middle	32.834.584	26.628.18 - 40.442.44	2023-07-162023-07-15
			Peak	61.562.697	41.142.24 - 91.893.05	2023-08-202023-08-11
Partly thawed 2	0.820.8	<0.001	Early	20.422.021	17.819.24 - 23.425.21	2023-06-232023-06-25
			Middle	53.453.96	46.447.02 - 61.461.93	2023-08-08
			Peak	92.993.89	71.572.48 - 120.8121.63	2023-08-30
Partly thawed 3	0.67	<0.001	Early	22.023.018	19.920.89 - 24.425.36	2023-06-132023-06-12
			Middle	54.654.945	49.750.33 - 60.159.98	2023-08-012023-07-21
			Peak	93.593.581	80.481.22 - 108.7107.82	2023-08-30

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Fully thawed 1	0.66	<0.001	Early	50.650.609	38.938.82 - 66.065.97	2023-05-19
			Middle	85.084.967	73.873.8 - 97.897.82	2023-06-21
			Peak	127.5128.204	109.5110.11 - 148.4149.27	2023-08-25
Fully thawed 2	0.66	<0.001	Early	40.140.038	33.933.88 - 47.347.31	2023-06-07
			Middle	77.777.439	65.965.64 - 91.691.37	2023-06-18
			Peak	120.2119.496	101.0100.37 - 142.9142.27	2023-08-2019
Fully thawed 3	0.830.8	<0.001	Early	35.439.268	32.336.12 - 38.942.7	2023-06-19
			Middle	116.9121.25	106.3110.57 - 128.5132.96	2023-08-045
			Peak	214.4220.851	180.0192.54 - 255.2253.33	2023-08-30

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Code and data availability

The belowground trait and vegetation survey data together with edaphic variables (Määttä and Malhotra, 2026) can be openly accessed at <https://doi.org/10.5281/zenodo.18269229>. The porewater CH₄ and δ¹³C data (Wilson et al., 2026) is available with open access at <https://doi.org/10.5281/zenodo.18363867>. The daily-aggregated automated chamber CH₄ flux data from the productive season and the peat moisture data are shown in the Appendices (Table C54 and Table C3, respectively). The full chamber CH₄ flux dataset will be published in the EMERGE-DB database (Bolduc et al., 2020) by May 2026 (<https://emerge-db.ase.ohio-state.edu/>). The R code used for data processing and analysis is available at <https://github.com/tiia-maa/Increased-plant-mediated-methane-transport-along-a-peatland-permafrost-thaw-gradient-git>.

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The R code used for data processing and analysis can be accessed via Zenodo (<https://doi.org/10.5281/zenodo.20718440>; Määttä, 2026).

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Author contributions

TM and AM conceptualized the study and prepared the original manuscript draft. Data curation and provision of resources was done by TM, RV, PC, SH, RW, SB, and JC. TM conducted the formal analysis, investigation, and visualization, and collected and processed the belowground trait data. Chamber CH₄ flux data was collected and provided by RV and PC, and

porewater gas data by SH, SB, RW and JC. AM and TM acquired funding for the study and coordinated the project. AM supervised the project. All authors contributed to the review and editing of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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