

Winter methane fluxes over boreal and Arctic environments

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Key Points:

- Boreal forest upland soils acted as net methane sink during winter.
- Boreal wetland soils acted as net winter methane source, while tundra wetlands emissions were generally low except for a few hotspots.
- In boreal forests, the soil liquid water content was one of the main environmental controls on winter methane fluxes.

Keywords:

Methane flux, Methane exchange, Arctic-boreal regions, Carbon cycle, Winter, Non-growing season.

32

33 Abstract

34 Unprecedented warming of Arctic–boreal regions (ABR) has poorly understood
35 consequences on carbon cycle processes. Uncertainties in annual methane (CH₄) budgets partly
36 arise because of limited data availability during winter. In this study, winter CH₄ flux
37 measurements were conducted using the snowpack diffusion gradient method over five ABR
38 ecosystem types in Canada and Finland: closed–crown and open–crown coniferous boreal forest,
39 boreal wetland and erect–shrub and prostrate–shrub tundra. Boreal forest uplands acted as net CH₄
40 sinks, while the boreal wetland acted as net CH₄ source during winter. We identified several
41 wetland tundra CH₄ emission hotspots and large spatial variability in boreal wetland CH₄
42 emissions. In the boreal forest uplands, soil liquid water content was identified as an important
43 environmental control of winter CH₄ fluxes. Our results indicate non–negligible winter CH₄ flux,
44 which must be accounted for in annual carbon balance and terrestrial biosphere models over ABR.

45 Plain Language Summary

46 The climate of our planet is closely linked to the atmospheric concentrations of greenhouse
47 gases such as carbon dioxide and methane that partially retain the energy coming from the Sun.
48 The Arctic and boreal regions are some of the environments that have been the least studied, mostly
49 because of their remoteness. In those environments, winter is the least studied period of the year
50 because of technical challenges posed by harsh winter conditions. Our study focused on winter
51 methane exchange between the snow–covered ground surface and the atmosphere in Arctic–boreal
52 regions. Methane is found in smaller quantities in the atmosphere compared to carbon dioxide but
53 with a much stronger warming potential. We observed that the boreal forests acted as a sink of
54 methane, removing methane from the atmosphere during winter. In contrast, boreal wetlands
55 emitted important amounts of methane into the atmosphere. We observed low methane emissions
56 in the Arctic tundra except for a few hotspots with high methane emissions. All those observations
57 show the variability of methane exchanges in different environments and highlight the importance
58 of understanding those exchanges to improve our ability to predict the role of Arctic–boreal
59 regions on the climate system.

60 1 Introduction

61 Methane (CH₄) exchange between the ground surface and the atmosphere in Arctic and boreal
62 biomes (hereafter called Arctic–boreal regions; ABR) play an important role in the global climate
63 with potentially important responses to a warming climate (Bekryaev et al., 2010; Kirschke et al.,
64 2013; Yvon–Durocher et al., 2014; Schuur et al., 2015; Dean et al., 2018; Röbger et al., 2022).
65 The response of ABR CH₄ fluxes to temperature is especially relevant since the ABR are warming
66 up to four times faster than the rest of the planet (Derksen et al., 2019; Rantanen et al., 2022). The
67 soils of ABR store a vast amount of labile organic matter due to inherently slow decomposition
68 rates, largely attributable to cold temperatures (Tarnocai et al., 2009; Deluca and Boisvenue, 2012;
69 Ravn et al., 2020). Therefore, altered CH₄ exchange rates due to ABR warming up could generate
70 potentially non–negligible, positive feedback to the global climate system (Natali et al., 2021;
71 Röbger et al., 2022; Schuur et al., 2022). Poor understanding of environmental controls on CH₄
72 exchange during winter constitutes a large source of uncertainty in the ABR CH₄ budget (McGuire
73 et al., 2012; Mastepanov et al., 2013; Treat et al., 2018).

74

75 The net soil CH₄ flux is a result of three groups of processes: production, oxidation, and
76 transport of CH₄. CH₄ in soils is produced by methanogens during organic matter decomposition
77 under mostly anoxic conditions, which typically occur in deeper soil layers or in water-saturated
78 environments (Zhang et al., 2017; Feng et al., 2020; Bastviken et al., 2023). In contrast, under
79 predominantly aerobic conditions, CH₄ is oxidized by methanotrophs as a source of energy and
80 carbon (Lai, 2009; Bastviken et al., 2023). Such aerobic conditions are often found in drier upper
81 soil layers in mineral upland soils. In well-drained soils, CH₄ oxidation typically exceeds
82 production resulting in a net soil CH₄ sink that removes CH₄ from the atmosphere (Lai, 2009; Lee
83 et al., 2023). In contrast, CH₄ oxidation in wetlands is lower than production resulting in net CH₄
84 emissions (Topp and Pattey, 1997; Roslev et al., 1997). Still, CH₄ oxidation in wetlands is an
85 important process that removes a large percentage of CH₄ produced in saturated soil layers before
86 it can reach the atmosphere (Oertel et al., 2016). During the oxidation process, CH₄ is oxidized to
87 carbon dioxide (CO₂) and water (H₂O). Methane transport, i.e., the movement of CH₄ from its
88 zone of production to the atmosphere by diffusion, ebullition, and plant-mediated transport also
89 plays an important role in mitigating CH₄ oxidation by limiting the time during which
90 methanotrophs can consume CH₄ (Bastviken et al., 2023). The vegetation composition of the
91 ecosystem has been shown to impact CH₄ fluxes by providing the organic matter substrate for CH₄
92 production, bypassing zones of CH₄ oxidation by plant-mediated transport, and by its indirect
93 impact on water table and thaw depth (King et al., 1998; Andresen et al., 2017; Bastviken et al.,
94 2023).

95
96 The majority of prior CH₄ studies in the ABR has focused on snow-free growing season fluxes
97 (e.g., Ullah et al., 2009; Zona et al., 2009; Helbig et al., 2016; Kuhn et al., 2021). The largest CH₄
98 flux measurement network, FLUXNET-CH₄, provides limited winter data from ABR due to the
99 failure of equipment in cold harsh conditions (Knox et al., 2019; Delwiche et al., 2021). The few
100 studies on winter CH₄ fluxes in the Arctic biome that exist showed that winter can contribute up
101 to 40 to 50% of the annual net CH₄ emissions (Zona et al., 2016; Treat et al., 2018; Rößger et al.,
102 2022; Ito et al., 2023). The length of winter typically increases with latitude and can span the
103 period from September to June. Most of the winter ABR CH₄ studies focus on wetlands and
104 peatlands where higher emissions are expected, with little attention to CH₄ sinks (Treat et al.,
105 2018). More studies of winter CH₄ fluxes have been carried out in the boreal biome than in the
106 Arctic biome, but even in the boreal biome, winter CH₄ flux measurements remain scarce
107 compared to growing season studies (Viru et al., 2020; Hiyama et al., 2021; Lee et al., 2023).
108 Overall, the limited data available on ABR CH₄ fluxes translates into limited knowledge of
109 environmental controls of winter CH₄ fluxes. This lack of knowledge is challenging terrestrial
110 biosphere models, often using CH₄ emission schemes developed for the growing season or lower
111 latitudes and more temperate environments which can be inaccurate when extrapolated to the ABR
112 carbon cycle (Fisher et al., 2014; Ito et al., 2023).

113
114 The goal of this study is to quantify winter CH₄ fluxes in different ABR ecosystems and
115 identify environmental controls on fluxes. Our study is based on 660 snowpack diffusion gradient
116 and supporting measurements (snowpack properties, soil temperature and liquid water content) at
117 five different ecosystems in Arctic and boreal biomes in Finland and Canada: a boreal wetland, a
118 closed-crown coniferous boreal forest stand, two open-crown coniferous boreal forest stands, an
119 erect-shrub tundra, and a prostrate-shrub tundra site. Spatially distributed measurements of

snowpack CH₄ diffusion gradients were performed during the 2020–2021, 2021–2022 and 2022–2023 winters (December to May).

2 Materials and Methods

2.1 Measurements sites

Five study sites characteristic of five ABR ecosystems were selected (Fig. S1; Table S1 and S2). Cambridge Bay (CB; Nunavut, Canada) was the northernmost site located in the Arctic biome dominated by lichen and prostrate shrub tundra. The CB site is constituted of mesic areas (CB–mes) and wetland areas (CB–wet) (Ponomarenko et al., 2019), Trail Valley Creek (TVC; Northwest Territories, Canada) is situated in the forest–tundra ecotone, the transitional zone between the boreal and Arctic biomes. TVC is dominated by erect shrub tundra with remaining tree patches (Martin et al., 2022; Voigt et al., 2023). Havikpak Creek (HPC; Northwest Territories, Canada) is located about 50 km south of TVC in an open–crown black spruce dominated forest stand, just south of the treeline (Krogh et al., 2017). Sodankylä (SOD, Lapland, Finland) is in the northern boreal biome. The SOD study site comprises two study zones: a closed–crown Scots pine–dominated forest stand (SOD–for) and adjacent open wetlands (*aapa mire*; SOD–wet) (Ilkonen et al., 2016). Montmorency Forest (MM; Québec, Canada) is the southernmost site located in a closed–crown balsam fir dominated boreal forest (Barry et al., 1988). The CB, TVC and HPC sites are underlain by continuous permafrost, while the MM and SOD sites are permafrost–free.

2.2 CH₄ flux calculation

In snow–covered regions, a vertical CH₄ diffusion gradient ($d[\text{CH}_4]/dz$; gC m^{−4}) is maintained through the snowpack as a result of CH₄ production, oxidation and transport in soils. Fick's first law for gas diffusion in porous media can be used to estimate CH₄ fluxes (F_{CH_4} ; mg C m^{−2} day^{−1}) from $d[\text{CH}_4]/dz$ (Sommerfeld et al., 1993; Zhu et al., 2014):

$$F_{\text{CH}_4} = -\varphi \cdot \tau \cdot D \cdot \frac{d[\text{CH}_4]}{dz} \quad (1)$$

where φ represents the snow porosity (unitless), τ the snow tortuosity (unitless) and D the diffusion coefficient of CH₄ through the air in m² day^{−1}. φ and τ can be estimated from snow density (ρ_{snow}) and snow liquid water content (θ) (Du Plessis and Masliyah 1991; Kinar and Pomeroy, 2015; Madore et al., 2022):

$$\varphi = 1 - \frac{\rho_{\text{snow}}}{\rho_{\text{ice}}} + \theta \cdot \left(\frac{\rho_{\text{water}}}{\rho_{\text{ice}}} - 1 \right) \quad (2)$$

$$\tau = \frac{1 - (1 - \varphi)^{2/3}}{\varphi} \approx \varphi^{1/3} \quad (3)$$

where ρ represents the density of snow, pure ice and water in g cm^{−3} ($\rho_{\text{water}} = 0.99984$ g cm^{−3} at $T = 0$ °C; Harvey et al., 2017). Ice density (ρ_{ice}) must be adjusted for ice temperature (T_{ice}) (Harvey et al., 2017):

$$\rho_{\text{ice}} = -0.0001 \cdot T_{\text{ice}} + 0.9168 \quad (4)$$

Standard diffusion coefficients of CH₄ are available in literature but must be corrected for temperature and pressure (Marrero and Mason, 1972; Massman, 1988):

$$D = 0.1859 \cdot \left(\frac{T}{T_o}\right)^{1.747} \quad (5)$$

where T is the air temperature and T_o is the freezing point (273.15 K). The diffusion gradient method assumes that gas fluxes are the result of simple, linear, gradient-induced diffusion through snowpack porosities (McDowell et al., 2000). If the gas flow is altered by ice crusts or dense snow layers, it could lead to a positive bias (i.e., F_{CH_4} overestimation; Seok et al., 2009). Such layers were rarely found in our study sites and did not cause the $d[CH_4]/dz$ to diverge from its linear relationship. In contrast, the diffusion gradient assumption also does not hold when strong wind events occur, decreasing snowpack CH₄ concentration through wind pumping and inducing a negative bias on CH₄ fluxes (Seok et al., 2009). Consequently, $d[CH_4]/dz$ was not measured in days following a strong wind event. Monitoring of F_{CH_4} at a few sampling locations did not show any relationship between F_{CH_4} and wind speed or atmospheric pressure (Mavrovic et al., 2023).

2.3 Data collection

The $d[CH_4]/dz$ was estimated by collecting gas samples along a vertical profile in the snowpack. Five gas samples were collected for each vertical profile: I) at 5 cm above the snowpack (ambient air), II) at 5 cm depth from the snowpack surface, III) at 1/3 of total snow depth, IV) at 2/3 of total snow depth and V) at the soil–snow interface. Snow pore gas was collected with a thin hollow stainless-steel rod (50–120 cm long, 4 mm outer diameter and 2 mm inner diameter). Gas was collected in a 60 mL syringe (Air–Tite Luer Lock, Virginia Beach, Virginia) connected to the rod via a three-way valve before being transferred into 12 mL hermetic glass vials (Labco Exetainer®, Labco Ltd., Lampeter, UK). CH₄ concentration was measured with a Licor LI–7810 CH₄/CO₂/H₂O Trace Gas Analyzer ($\sigma < 0.03\%$ at 2 ppm; LI–COR Biosciences, Lincoln, Nebraska, US) using an open-loop method with a continuous flow of a 1.1 ppm CH₄ calibration gas (Linde Canada, Ottawa, Ontario). The CH₄ concentration of gas samples was calculated based on a calibration curve of gas standards ranging from 0 to 10 ppm of CH₄. At each site, several sampling locations were selected to cover the full range of vegetation types and snowpack characteristics, covering defined areas of 0.25–4 km². At each sampling location, 2 to 4 replicate profiles were measured within 2–3 m to ensure sampling repeatability.

After gas sampling, a vertical profile of snow and soil properties was measured to calculate snow porosity, tortuosity and the CH₄ diffusion coefficient. Snow properties were measured at every 5 cm including snow temperature (Snowmetrics digital thermometer; a tenth of a degree resolution), snow density (Snowmetrics digital scale, 100 and 250 cm³ snow cutters; $\sigma(\rho_{\text{snow}}) \approx 9\%$; Proksch et al., 2016), snow liquid water content (hand test from Fierz et al., 2009) and snow stratigraphy. Near-surface soil temperature (T_{soil}) was measured at 1 cm depth below the soil–snow interface, and three measurements within 1 m of T_{soil} were averaged. An uncertainty assessment was conducted to evaluate CH₄ flux precision based on the snowpack diffusion gradient method; the detailed method can be found in the supporting information (Table S3 and Fig. S2). An empirical soil liquid water and ice mixing model following Zhang et al. (2010) was used to calculate soil volumetric liquid water content (LWC); the detailed calculation can be found in the supporting information.

3 Results

3.1 Winter methane fluxes across ABR sites

Our results showed mostly low to negligible CH_4 emissions in tundra sites (CB and TVC) and open-crown boreal forest (HCP). At those sites, fluxes ranged from $-0.21 \text{ mg C m}^{-2} \text{ day}^{-1}$ (CH_4 uptake) to $0.33 \text{ mg C m}^{-2} \text{ day}^{-1}$ (CH_4 emissions) with a mean rate of $0.03 \pm 0.08 \text{ mg C m}^{-2} \text{ day}^{-1}$ (mean \pm standard deviation), except for a few hotspots at CB that emitted CH_4 up to $1.46 \text{ mg C m}^{-2} \text{ day}^{-1}$ with a mean rate of $0.78 \pm 0.31 \text{ mg C m}^{-2} \text{ day}^{-1}$ (Fig. 1). The winter CH_4 hotspots were revisited 10 times over a period of 8 weeks and consistently displayed high CH_4 emissions.

Several vegetation types were found in the Arctic tundra sites of CB and TVC. The main differences between CH_4 fluxes among vegetation types at CB followed soil water regimes as divided into mesic and wetland areas (Fig. 1). We observed some differences in the ranges and means of CH_4 fluxes among TVC vegetation types, although those differences were small compared to the variability between study sites (Fig. S3). The TVC vegetation types surveyed by ascending mean CH_4 fluxes are as follows: dwarf shrub, black spruce patch, riparian shrub, lichen, tussock, polygon, and tall shrub. The closed-crown coniferous boreal forest sites showed mean CH_4 uptake rates throughout winter of $-0.43 \pm 0.34 \text{ mg C m}^{-2} \text{ day}^{-1}$ (MM) and $-0.47 \pm 0.26 \text{ mg C m}^{-2} \text{ day}^{-1}$ (SOF-for). The SOD-wet boreal wetland displayed high CH_4 emissions throughout winter, with rates up to $48.51 \text{ mg C m}^{-2} \text{ day}^{-1}$ and an average of $4.57 \pm 7.34 \text{ mg C m}^{-2} \text{ day}^{-1}$. The boreal wetland F_{CH_4} at SOD-for were at least one order of magnitude higher than any other site in this study. The boreal wetland sampling locations displayed an important spatial variability of F_{CH_4} with some sampling locations emitting CH_4 at average rates up to 50 times higher than the lowest ones (Fig. S4).

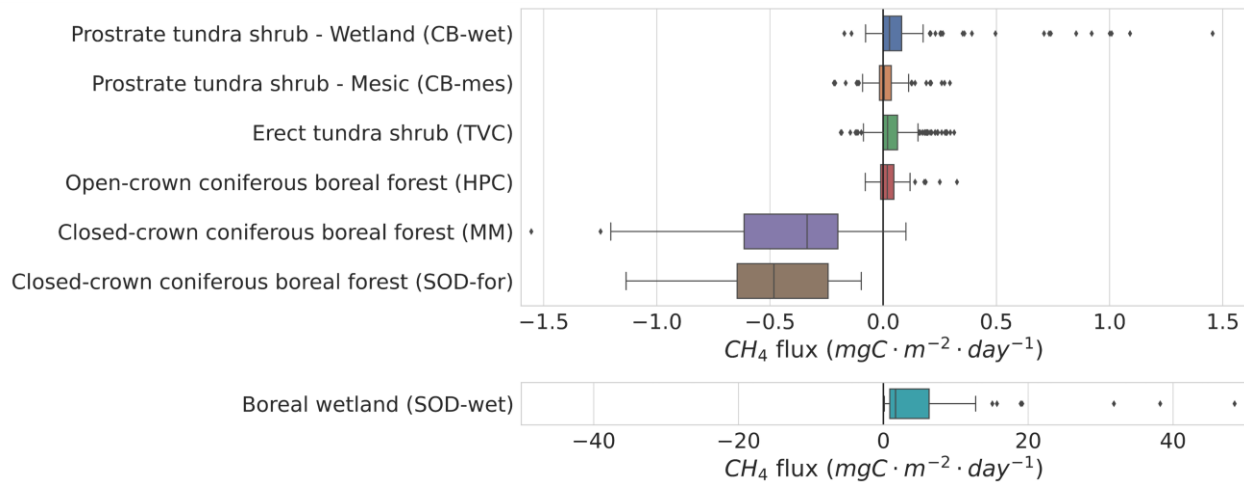


Figure 1. CH_4 flux across the study sites. Outliers were defined as $F_{\text{CH}_4} > Q3 + 1.5 \text{ IQR}$ where $Q3$ is the third quartile and IQR the interquartile range. The F_{CH_4} from the boreal wetland is shown on a separate axis since the range of F_{CH_4} is of a different order of magnitude.

3.2 Environmental controls of winter methane fluxes

Statistical analyses were performed to identify the environmental variables (i.e., T_{soil} , soil LWC, vegetation type and snow variables) controlling CH_4 fluxes at both the site-level and over the entire dataset in the different northern ecosystems. The statistical analysis approach included correlation, regression and machine learning (i.e., Random Forest). For tundra sites (i.e., CB and TVC), as the CH_4 fluxes were relatively small, none of these variables proved statistically significant (e.g., Fig. 3 for T_{soil}). The correlation between F_{CH_4} and snow variables was low at all study sites ($R^2 < 0.13$ for total snow height, SWE and mean snow density). However, at the closed-crown coniferous boreal forest sites of MM and SOD-for, our results show a site-specific linear relationship between winter F_{CH_4} and soil LWC (Fig. 2). The correlation between F_{CH_4} and T_{soil} at 1 cm depth was low since T_{soil} had a narrow range during the measurement campaigns at MM and SOD-for, being around freezing point for all measurements ($R^2 = 0.035$; Fig. 3). MM and SOD-for boreal forest uplands were the only two sites with near-surface T_{soil} close enough to 0°C to allow the coexistence of ice and liquid water in the soil. Water-saturated organic layers also occurred at the boreal wetland of SOD-wet, but the liquid water was trapped under a top-layer made mostly of solid ice with a thickness of several centimeters.

One sampling location at MM displayed different soil properties than the other sampling locations because of its thick organic soil layer and high soil moisture regime due to its location near the bottom of a microtopographic depression (Fig. 2). Other MM sampling locations with a thin organic layer shared a similar soil composition dominated by sandy loam mineral soils. The MM thick organic layer sampling location alternates between a CH_4 source or sink throughout the snow-covered season.

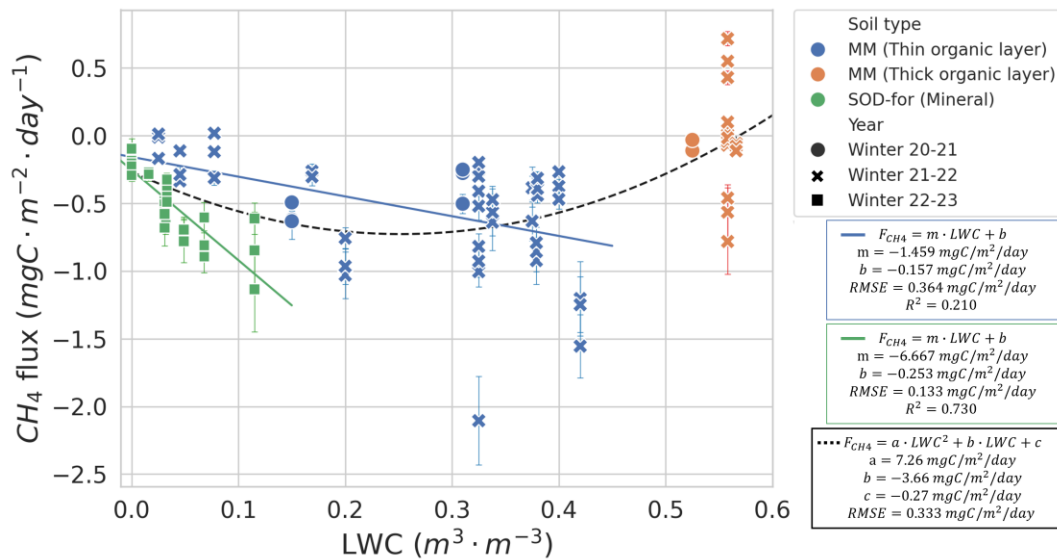


Figure 2. CH_4 flux as a function of soil volumetric liquid water content (LWC) at the Montmorency Forest (MM) and Sodankylä (SOD-for) boreal forest uplands study sites, the only sites where liquid water was present during our winter campaigns. A linear regression was fitted for the SOD-for boreal forest uplands data and MM data, excluding the thick organic layer site. There is only one sampling location for the MM thick organic layer, whereas there are 9 sampling locations for the MM thin organic layer and 9 for the SOD-for. A polynomial regression was fitted to all data.

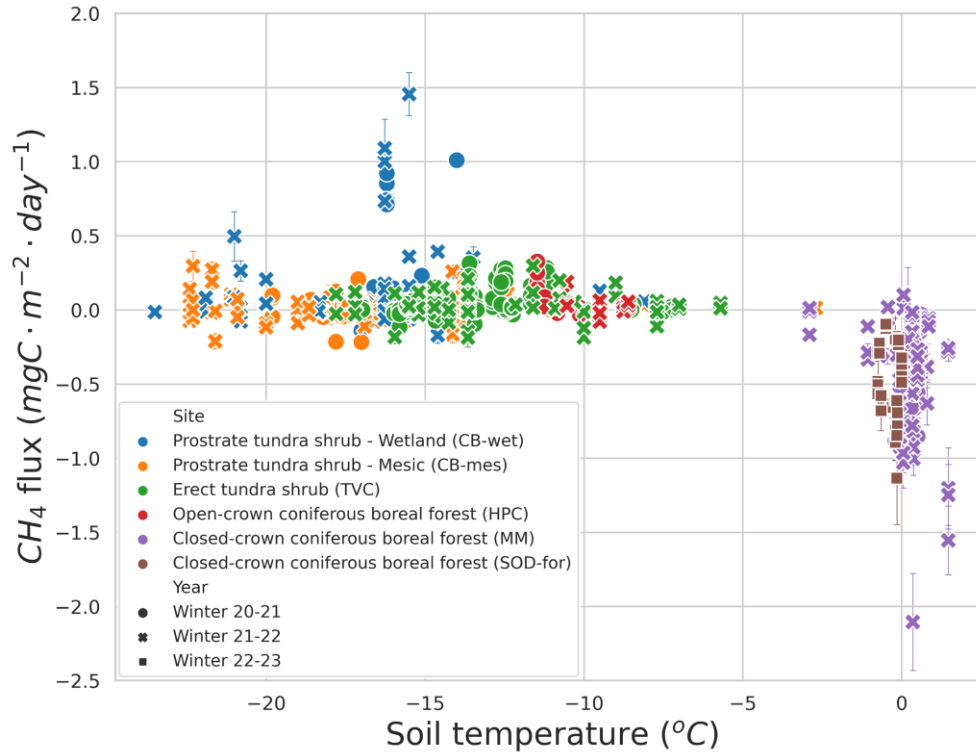


Figure 3. CH₄ flux as a function of soil temperature at 1 cm depth at the study sites of Cambridge Bay (CB), Trail Valley Creek (TVC), Havikpak Creek, Montmorency Forest (MM) during winter 2020–2021 and 2021–2022, and at Sodankylä (SOD–for).

4 Discussion

CH₄ flux regimes were previously observed mostly during the growing season, whereas our study focused on winter CH₄ fluxes. Our findings support the prevailing notion of boreal forest upland soils generally acting as CH₄ sinks (Lai, 2009; Lee et al., 2023) and wetlands acting as CH₄ sources (Oertel et al., 2016), and that these patterns hold true for the winter period. The winter CH₄ fluxes at the upland tundra sites were too low to classify these sites as either net sources or net sinks. The study sites with milder climates, MM and SOD, displayed the highest CH₄ fluxes, whether as CH₄ sink or source (Fig. 1). These sites have higher mean annual air temperatures (1.6 to 2.0 °C compared to –12.5 to –6.6 °C at CB, TVC, and HPC), no permafrost, longer growing seasons (94 to 113 days compared to 168 to 171 days at CB, TVC, and HPC), and higher annual precipitation (507 to 1293 mm compared to 152 to 198 mm at CB, TVC, and HPC). We also identified a few CH₄ emission hotspots in Arctic tundra wetlands during winter that emitted on average about 26 times more CH₄ than the average of other sample locations (0.78 vs. 0.03 mg C m^{–2} day^{–1}). All those CH₄ emission hotspots were found in wetland environments with high soil nutrient content (soil nutrient content determined from Ponomarenko et al., 2019). However, it is important to note that not all sampling locations in wetlands with high soil nutrient content exhibited CH₄ emission hotspots ($F_{CH_4} \geq 0.35$ mg C m^{–2} day^{–1}); only 37.5% of wetland sampling locations exhibited high CH₄ emissions. Although we did not determine spatially integrated flux estimates for our sites, these hotspots may dominate the winter CH₄ flux budget.

Our results do not show a strong correlation between winter CH₄ fluxes and T_{soil} or snow parameters, unlike some previous studies that have found a correlation between CH₄ flux and sub-zero T_{soil} (Rößger et al., 2022). It is possible that surface T_{soil} at 1 cm depth in our study did not correlate with CH₄ fluxes, but that deeper T_{soil} could have a stronger correlation since most CH₄ production occurs in deeper soil layers (Henneron et al., 2022; Li et al., 2023). If further investigations show that deeper T_{soil} still does not correlate strongly with winter CH₄ fluxes in ABR, several terrestrial biosphere models would have to reassess how CH₄ fluxes are estimated as most use T_{soil} or T_{air} as a main control of CH₄ flux computation. However, it is also possible that other factors are masking the temperature dependency of winter CH₄ fluxes, such as a strong inter-site variability of fluxes between the measurement locations at different land cover and vegetation types. According to Lee et al. (2023), soil organic carbon content has also been shown to be an important control on CH₄ sinks of forested regions which might be why the rate of CH₄ uptake increase with soil LWC is site-specific and the temperature dependence weak. We observed a weak correlation between F_{CH₄} and F_{CO₂} fluxes (measured in our previous study; Mavrovic et al., 2023) at the boreal forest upland sites (Fig. S5), which might be an indication of increased CH₄ uptake with higher soil carbon substrate availability or soil microbial activity as discovered recently for growing season CH₄ uptake (Voigt et al. 2023). The slower diffusion of CH₄ to the atmosphere in winter due to the fraction of soil pores filled with ice in frozen soils might also be contributing to masking the temperature dependency of winter CH₄ fluxes assuming again that an important fraction of CH₄ emissions occurs deeper than the measured soil temperature.

The boreal forest upland sites (MM and SOD-for) displayed a relatively strong correlation between F_{CH₄} and soil LWC ($R^2 = 0.21$ and 0.73 , respectively), although the rate of CH₄ uptake increases with soil LWC seemed to be site-specific. Despite differences in vegetation, soil, latitude, and precipitation, both sites displayed a similar range of net CH₄ uptake from the atmosphere. The main common characteristics between MM and SOD are the length of the growing season and the mean average air temperature (Table S2). MM and SOD are also the only study sites where the soil remained mostly unfrozen throughout winter. Unfrozen, well-drained soils have more pore space than frozen ones because of ice volume expansion. Larger pore space benefits CH₄ oxidation through increased diffusion rates (Ball et al., 1997; Smith et al., 2000). The MM and SOD-for sites also displayed a similar range of CO₂ emissions during winter, stressing that MM and SOD-for sites have comparable carbon flux regimes (Fig. S6; Mavrovic et al., 2023).

The SOD-wet boreal wetland CH₄ emissions were high but seemed to be limited by transport through the thick solid ice that formed in the wetland's upper layer. In April, during snowmelt, CH₄ concentrations under the 10–30 cm ice layer on top of the soil reached up to 1000 ppm at some sampling locations. The non-negligible F_{CH₄} observed at the wetland indicates that the thick ice layer is porous but the underlying CH₄ production is higher than what is released into the atmosphere, at least for this part of winter. The trapped CH₄ is probably released during ice melt, which is coherent with previous studies that showed bursts of CH₄ emissions during spring melt (Song et al., 2012; Raz-Yaseef et al., 2016). Further investigation would be required to determine if the strong spatial variability observed in the boreal wetland is mainly due to variability in the upper ice layer porosity or variability in the underlying CH₄ production.

The shoulder seasons (i.e., autumn freeze and spring thaw) are important periods of change in CH₄ exchange regimes with an important contribution to the annual CH₄ budget (Arndt et al., 2020; Bao et al., 2021). Whereas this study presents results from the sites of MM, CB, and SOD—wet covering most of the winter with monthly flux measurement, the flux measurements of the study sites of TVC, HPC, and SOD—for covered only short winter campaigns (Table S2). Furthermore, the snowpack diffusive gradient method is limited to measurements within the snow-covered period. Further investigation of shoulder seasons CH₄ fluxes should be conducted to provide a better understanding of the inter-annual variability of the carbon cycle in ABR. Soil biogeochemical properties such as the quantity and quality of available carbon compounds were not addressed in this study but were shown to be important environmental controls of CH₄ fluxes (Aronson et al., 2013; Kharitonov et al., 2021; Lee et al., 2023; Voigt et al., 2023). Soil biogeochemical properties are generally strongly correlated with plant community composition and thus CH₄ flux (Bastviken et al., 2023). Biogeochemical analyses, as well as studies on microbial community composition and functioning during winter might help to explain the site-specific linear relationship between CH₄ flux and soil LWC, and, importantly, the lack of temperature dependence we observed in our study. Additionally, our study points towards the relevance of ice conditions in wetlands for understanding winter CH₄ fluxes and highlights the importance of an integrative view of CH₄ fluxes and soil properties.

5 Conclusions

We measured *in situ* winter CH₄ flux over five Arctic and boreal sites in Canada and Finland with diverse ecosystem types. Our findings indicate non-negligible winter F_{CH₄}, which must be accounted for in annual carbon balance and terrestrial biosphere models over ABR. Although F_{CH₄} of most Arctic sites was low, emission hotspots were observed in tundra and boreal wetlands. In the boreal forest uplands, soil liquid water content was identified as an important environmental control on net CH₄ uptake from the atmosphere, but the rate of CH₄ uptake increase with soil LWC dependency was different for the two boreal forest uplands study sites. It will be important to investigate if this site-specific LWC dependency could be related to other environmental controls such as soil physical-chemical properties and vegetation composition. The boreal wetland site displayed high CH₄ emissions throughout winter with high spatial variability, stressing the importance of further investigating the magnitude of these emissions from other sites and wetland ecotypes. Contrary to some other studies, we found a lack of temperature dependence on winter CH₄ flux across the different ABR ecosystems investigated, this is a significant finding that should be investigated further since several terrestrial biosphere models use soil temperature as a main control of winter CH₄ fluxes. Our study stresses the importance of considering ABR winter CH₄ flux to accurately calculate the carbon budget in these sensitive environments.

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Open Research

All data presented in this article can be found in the following repository:

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Supporting Information

Study sites



Figure S1. Study site locations. The Arctic biome is delimited following the Conservation of Arctic Flora and Fauna (CAFF) working group of the Arctic Council (Arctic SDI Catalogue, Identifier: 2ad7a7cb–2ad7–4517–a26e–7878ef134239, 2017) and the boreal biome is delimited following Potapov et al. (2008). Permafrost extent (Brown et al., 2002) is estimated in percent area: continuous (>90–100%), discontinuous (>50–90%), sporadic (>10–50%) and isolated patches ($\leq 10\%$). Figure modified from Mavrovic et al. (2023).

Table S1. Study sites with the number of sampling locations and CH₄ flux measurement (N) for each site. Some study sites have more sampling locations than others because there were more vegetation types and a larger area to cover. Overall, every type of vegetation had 5–10 sampling locations. Table modified from Mavrovic et al. (2023).

Site	Acronym	Location	Latitude/ longitude	Sampling locations	N	Measurement months	Site reference
Cambridge Bay	CB	Nunavut, Canada	69°13'N 104°54'W	47	230	2021: 04, 12 2022: 01-05	Ponomarenko et al., 2019
Trail Valley Creek	TVC	Northwest Territories, Canada	68°46'N 133°28'W	34	152	2021: 03, 12 2022: 03	Grünberg et al., 2020
Havikpak Creek	HPC	Northwest Territories, Canada	68°19'N 133°31'W	5	30	2021: 03, 04 2022: 03	Krogh et al., 2017
Montmorency Forest	MM	Quebec, Canada	47°18'N 71°10'W	12	110	2021: 01, 02, 12 2022: 01-05	Barry et al., 1988
Sodankylä	SOD	Lapland, Finland	67°22'N 26°38'E	30	138	2022: 02-04 2022-2023: 12-05	Ikonen et al., 2016

Table S2. Vegetation, soil, and climate properties of the study sites. Mean annual air temperature, annual precipitation, and growing season length were evaluated for the years with CH₄ flux measurements (2021–2022 for CB, TVC, HPC and MM; 2022 for SOD). Growing season length was estimated from the last to the first day of frost using a 5–day running–average daily mean air temperature (Tanja et al., 2003).

Site	Ecosystem	Dominant specie	Acronym	Soil layers	Mean Annual T _{air}	Annual Precipitation	Growing Season Length	Permafrost
Cambridge Bay	Prostrate tundra shrubs	Lichen and moss	CB-mes	Mesic: 0-5 cm organic over dry mineral	-12.5 °C	152 mm	94 days	Continuous
	Open wetland	Sedge fen	CB-wet	Wetland: 10-20 cm organic over wet mineral (clay)				
Trail Valley Creek	Erect tundra shrubs	Schurb, lichen, moss and tussock	TVC	30-60 cm organic (peat) over mineral	-7.8 °C	175 mm	111 days	Continuous
Havikpak Creek	Open-crown coniferous boreal forest	Black spruce	HPC	5-50 cm organic (peat) over mineral (silty clay)	-6.6 °C	198 mm	113 days	Continuous
Montmorency Forest	Closed-crown coniferous boreal forest	Balsam fir	MM	4-7 cm litter over 7-13 cm organic over wet mineral (sandy loam)	2.0 °C	1293 mm	171 days	Absent
Sodankylä	Closed-crown coniferous boreal forest	Scots pine	SOD-for	0-5 cm organic over dry mineral (sand)	1.6 °C	507 mm	168 days	Absent
	Open wetland	Fen and bog	SOD-wet	> 120 cm organic (peatland)				

CH₄ flux uncertainty assessment

Sources of uncertainties for F_{CH_4} can be subdivided into four categories: gas concentration estimates, gas transfer/transport/storage, snow properties estimates and $d[CH_4]/dz$ estimates. The uncertainty on $[CH_4]$ was evaluated from the gas analyzer precision as assessed by the manufacturer. $[CH_4]$ uncertainty was further tested using calibration gases. The gas transfer, transport and storage protocols were tested using calibration gases. The $d[CH_4]/dz$ linear regression uncertainties were evaluated using the standard deviation from the Pearson correlation coefficient ($\sigma = \sqrt{(1 - R^2)/(N - 1)}$; Bowley, 1928). F_{CH_4} uncertainty was calculated by uncertainty propagation from $d[CH_4]/dz$ and snow density uncertainties.

The F_{CH_4} uncertainty assessment showed that the two main sources of uncertainty are associated with snow density measurements ($\sigma(\rho_{snow}) \approx 9\%$; Proksch et al., 2016) and with $d[CH_4]/dz$ (mean $R^2 = 0.901$ ($\sigma = 0.135$) for $F_{CH_4} \geq 0.05 \text{ mg C m}^{-2} \text{ day}^{-1}$; $N = 339$) (Table S1). The mean F_{CH_4} uncertainty can be estimated at 16.89% for data from CB, TVC, MM and SOD—for boreal forest, and 3.76% for data from SOD—wet boreal wetland (Fig. S1).

Table S3. F_{CH_4} uncertainty sources. $[CH_4]$ precision was evaluated at a concentration of 2 ppm.

F_{CH_4} uncertainty source	Uncertainty
$[CH_4]$ estimate	
· LI-7810 precision	0.6 ppm (0.03%)
· Measurement stability	0.001 ppm (0.05%; $N=169$)
· Reference gas	0.018 ppm (1%)
· Calibration fit	0.005 ppm (0.25%; $N=8$; $\sigma = 0.067\%$)
· Transfer, transport and storage test	0.012 ppm (0.63%; $N=5$)
Snow density ($\text{kg} \cdot \text{m}^{-3}$)	9%
$d[CH_4]/dz$ linear regression ($\text{gC} \cdot \text{m}^{-4}$)	17.66% ($N=339$; $\sigma = 17.14\%$)

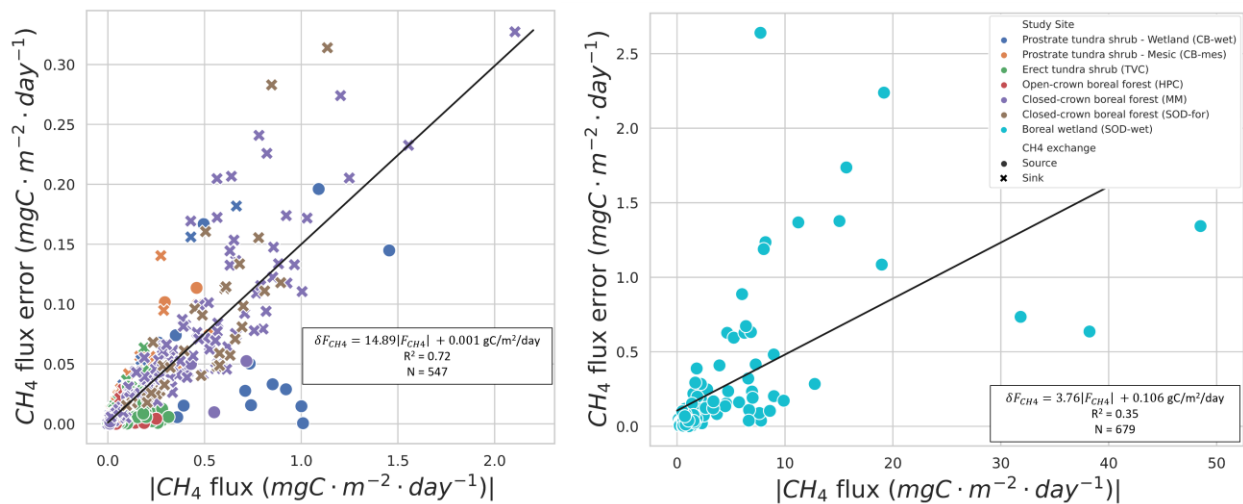


Figure S2. F_{CH_4} uncertainty relationship to $|F_{CH_4}|$ for the five study sites: Montmorency Forest (MM), Cambridge Bay (CB), Trail Valley Creek (TVC), Havikpak Creek (HPC) and Sodankylä (SOD).

Soil liquid water content calculation

A mix of ice and liquid water can coexist in the soil pore space when soil temperature is around 0 °C. MM and SOD-for are the only sites where the conditions allowed the coexistence of ice and liquid water in the soil pore space of soil upper layers for most of winter. MM was equipped with permanent TEROS 12 Soil Moisture Sensors (METER Group) at 5 cm depth. At SOD-for, instantaneous soil LWC measurements were conducted along with the snow and soil properties using a ML3 ThetaProbe Soil Moisture Sensor (Delta-T Devices). Zhang et al. (2010) empirical soil liquid water and ice mixing model was used to calculate soil volumetric liquid water content (LWC) and ice fraction from permittivity probes:

$$LWC = a \cdot \frac{\rho_b}{\rho_w} \cdot |T_{soil}|^{-b} \quad (5)$$

$$\ln a = 0.5519 \cdot \ln SSA + 0.2618 \quad ; \quad \ln b = -0.264 \cdot \ln SSA + 0.3711 \quad (6)$$

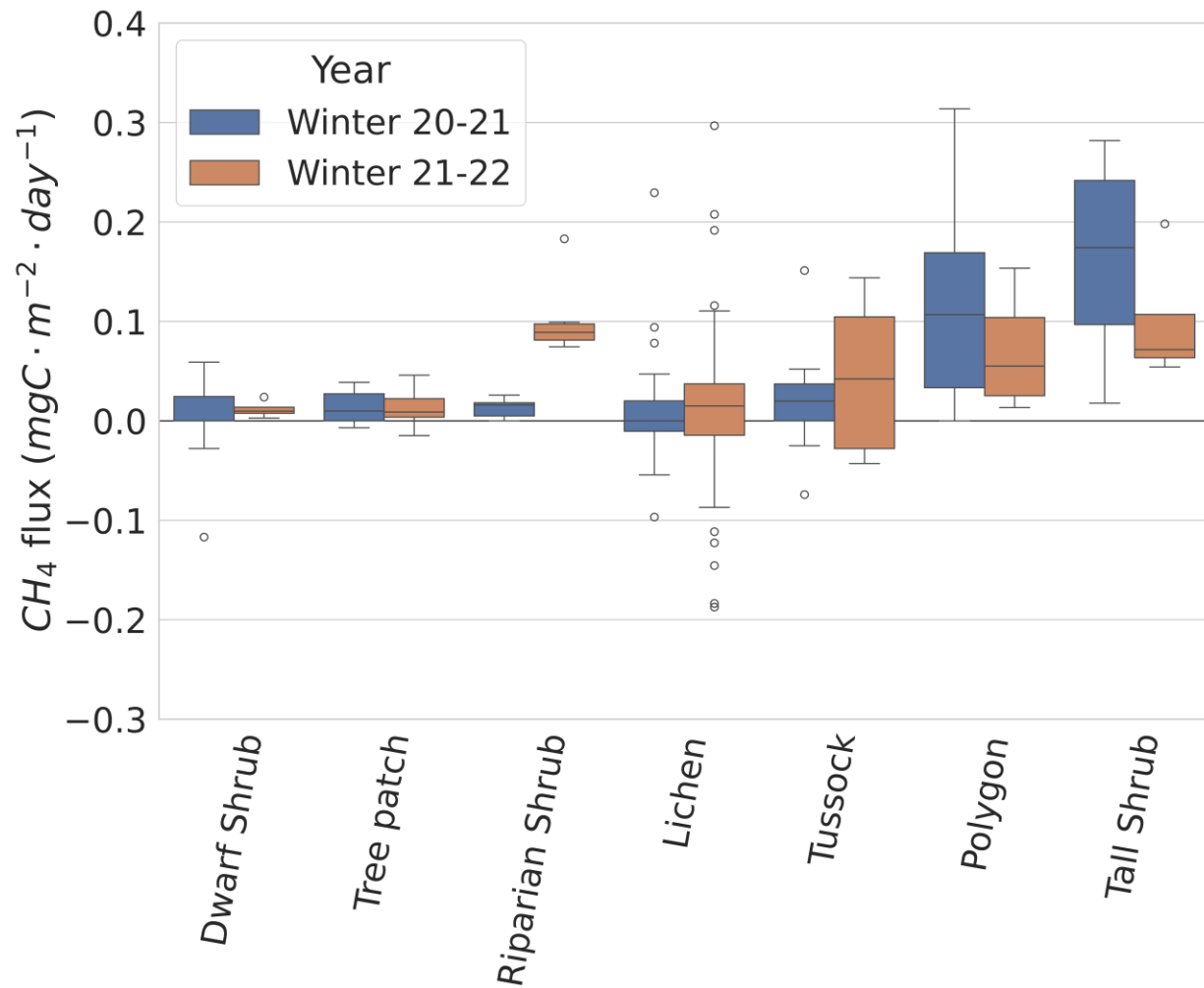
where ρ_w and ρ_b (g cm^{-3}) represent liquid water and soil bulk density respectively, T_{soil} (°C) represents soil temperature, SSA (m^{-1}) represents soil particles specific surface area described by Fooladman (2011).

$$SAA = 3.89 \cdot d_g^{-0.905} \quad (7)$$

$$\ln d_g = f_c \cdot \ln M_c + f_{si} \cdot \ln M_{si} + f_{sa} \cdot \ln M_{sa} \quad (8)$$

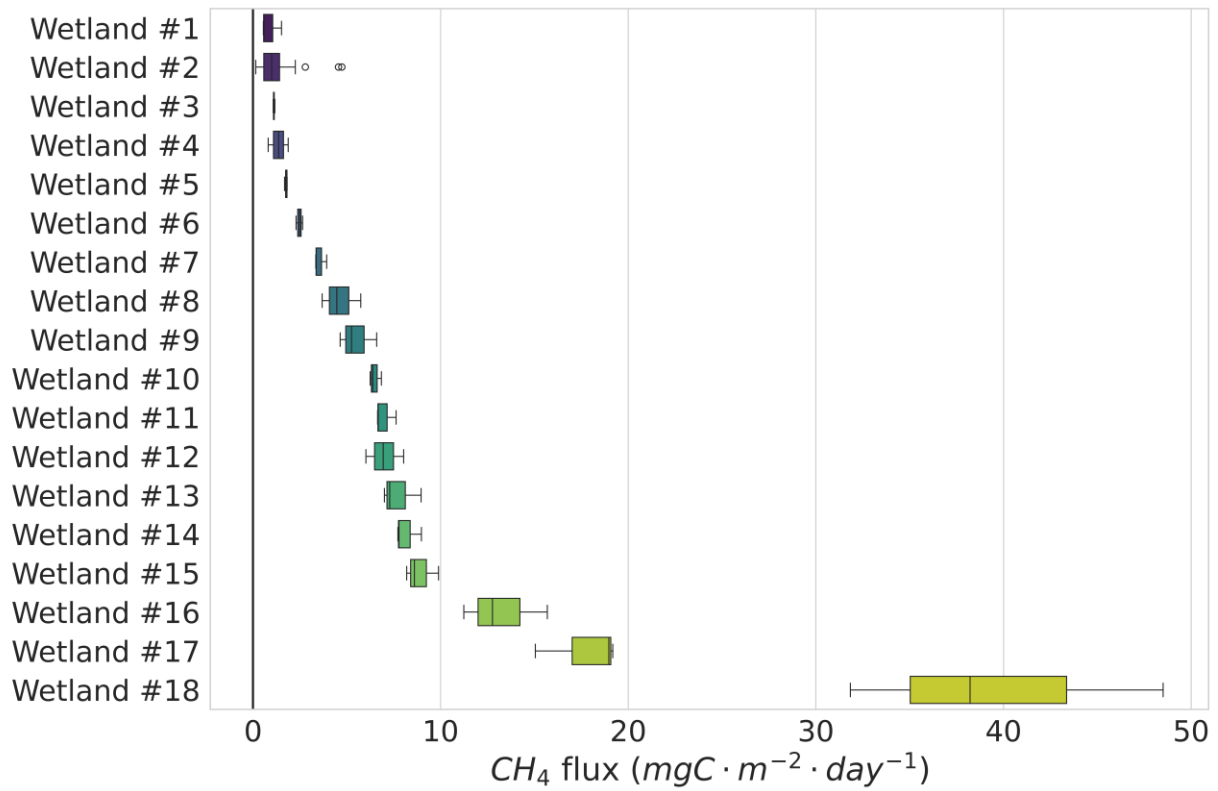
where d_g represents the soil geometric mean particle-size diameter (mm), f and M represent soil fractions and mean particle-size diameter (mm) of soil components respectively. The model's soil components are clay ($M_c = 0.001$ mm), silt ($M_{si} = 0.026$ mm) and sand ($M_{sa} = 1.025$ mm).

855 **CH₄ flux across vegetation types at Trail Valley Creek**



856 **Figure S3.** CH₄ flux across vegetation types at Trail Valley Creek. Vegetation types were not
 857 distinguished by soil moisture classes (like at the Cambridge Bay study site) since the information
 858 was not available at the scale of the sampling locations.
 859

860 **Spatial variability of boreal wetland CH₄ fluxes**



861 **Figure S4.** CH₄ flux spatial variability in the boreal wetland at the Sodankylä study site (SOD–
 862 wet).
 863

CH₄ fluxes relationship to CO₂ fluxes

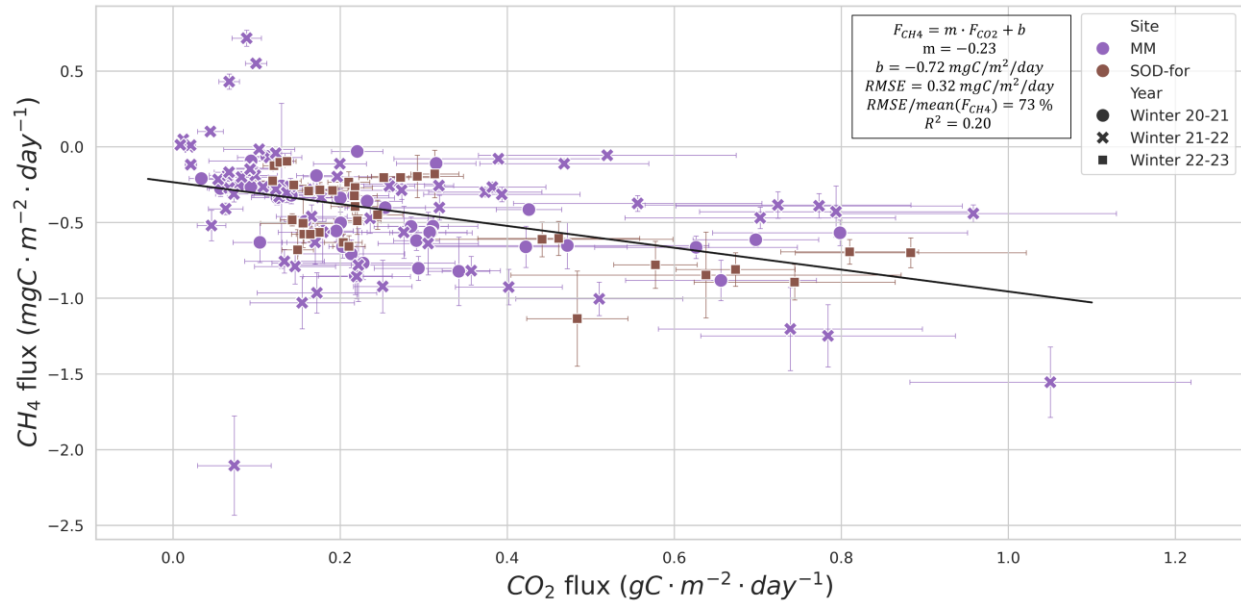


Figure S5. CH₄ flux as a function of CO₂ flux at the Montmorency Forest (MM) and Sodankylä (SOD-for) boreal forest uplands study sites. CO₂ flux data were estimated using the snowpack diffusive gradient method, the same method that was used to obtain the CH₄ flux data in this study. Details about CO₂ flux calculation can be found in Mavrovic et al. (2023).

Boreal forest CO₂ fluxes

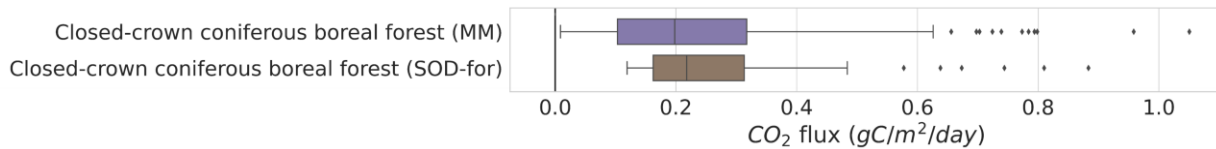


Figure S6. CO₂ flux at Montmorency Forest (MM) during winter 2020–2021 and 2021–2022, and at Sodankylä (SOD-for) during winters 2021–2022 and 2023. CO₂ flux data were estimated using the snowpack diffusive gradient method, the same method that was used to obtain the CH₄ flux data in this study. Details about CO₂ flux calculation can be found in Mavrovic et al. (2023). Outliers were defined as $F_{CO_2} > Q_3 + 1.5 \text{ IQR}$ where Q_3 is the third quartile and IQR the interquartile range.