Winter methane fluxes over boreal and Arctic environments

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Abstract

Unprecedented warming of Arctic–boreal regions (ABR) has poorly understood consequences on carbon cycle processes. Uncertainties in annual methane (CH\textsubscript{4}) budgets partly arise because of limited data availability during winter. In this study, winter CH\textsubscript{4} flux measurements were conducted using the snowpack diffusion gradient method over five ABR ecosystem types in Canada and Finland: closed–crown and open–crown coniferous boreal forest, boreal wetland and erect–shrub and prostrate–shrub tundra. Boreal forest uplands acted as net CH\textsubscript{4} sinks, while the boreal wetland acted as net CH\textsubscript{4} source during winter. We identified several wetland tundra CH\textsubscript{4} emission hotspots and large spatial variability in boreal wetland CH\textsubscript{4} emissions. In the boreal forest uplands, soil liquid water content was identified as an important environmental control of winter CH\textsubscript{4} fluxes. Our results indicate non–negligible winter CH\textsubscript{4} flux, which must be accounted for in annual carbon balance and terrestrial biosphere models over ABR.
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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.
Abstract

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

Plain Language Summary

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

1 Introduction

Methane (CH4) exchange between the ground surface and the atmosphere in Arctic and boreal biomes (hereafter called Arctic–boreal regions; ABR) play an important role in the global climate with potentially important responses to a warming climate (Bekryaev et al., 2010; Kirschke et al., 2013; Yvon–Durocher et al., 2014; Schuur et al., 2015; Dean et al., 2018; Rößger et al., 2022). The response of ABR CH4 fluxes to temperature is especially relevant since the ABR are warming up to four times faster than the rest of the planet (Derksen et al., 2019; Rantanen et al., 2022). The soils of ABR store a vast amount of labile organic matter due to inherently slow decomposition rates, largely attributable to cold temperatures (Tarnocai et al., 2009; Deluca and Boisvenue, 2012; Ravn et al., 2020). Therefore, altered CH4 exchange rates due to ABR warming up could generate potentially non–negligible, positive feedback to the global climate system (Natali et al., 2021; Rößger et al., 2022; Schuur et al., 2022). Poor understanding of environmental controls on CH4 exchange during winter constitutes a large source of uncertainty in the ABR CH4 budget (McGuire et al., 2012; Mastepanov et al., 2013; Treat et al., 2018).
The net soil CH$_4$ flux is a result of three groups of processes: production, oxidation, and transport of CH$_4$. CH$_4$ in soils is produced by methanogens during organic matter decomposition under mostly anoxic conditions, which typically occur in deeper soil layers or in water–saturated environments (Zhang et al., 2017; Feng et al., 2020; Bastviken et al., 2023). In contrast, under predominantly aerobic conditions, CH$_4$ is oxidized by methanotrophs as a source of energy and carbon (Lai, 2009; Bastviken et al., 2023). Such aerobic conditions are often found in drier upper soil layers in mineral upland soils. In well–drained soils, CH$_4$ oxidation typically exceeds production resulting in a net soil CH$_4$ sink that removes CH$_4$ from the atmosphere (Lai, 2009; Lee et al., 2023). In contrast, CH$_4$ oxidation in wetlands is lower than production resulting in net CH$_4$ emissions (Topp and Pattey, 1997; Roslev et al., 1997). Still, CH$_4$ oxidation in wetlands is an important process that removes a large percentage of CH$_4$ produced in saturated soil layers before it can reach the atmosphere (Oertel et al., 2016). During the oxidation process, CH$_4$ is oxidized to carbon dioxide (CO$_2$) and water (H$_2$O). Methane transport, i.e., the movement of CH$_4$ from its zone of production to the atmosphere by diffusion, ebullition, and plant–mediated transport also plays an important role in mitigating CH$_4$ oxidation by limiting the time during which methanotrophs can consume CH$_4$ (Bastviken et al., 2023). The vegetation composition of the ecosystem has been shown to impact CH$_4$ fluxes by providing the organic matter substrate for CH$_4$ production, bypassing zones of CH$_4$ oxidation by plant–mediated transport, and by its indirect impact on water table and thaw depth (King et al., 1998; Andresen et al., 2017; Bastviken et al., 2023).

The majority of prior CH$_4$ studies in the ABR has focused on snow–free growing season fluxes (e.g., Ullah et al., 2009; Zona et al., 2009; Helbig et al., 2016; Kuhn et al., 2021). The largest CH$_4$ flux measurement network, FLUXNET–CH$_4$, provides limited winter data from ABR due to the failure of equipment in cold harsh conditions (Knox et al., 2019; Delwiche et al., 2021). The few studies on winter CH$_4$ fluxes in the Arctic biome that exist showed that winter can contribute up to 40 to 50% of the annual net CH$_4$ emissions (Zona et al., 2016; Treat et al., 2018; Rößger et al., 2022; Ito et al., 2023). The length of winter typically increases with latitude and can span the period from September to June. Most of the winter ABR CH$_4$ studies focus on wetlands and peatlands where higher emissions are expected, with little attention to CH$_4$ sinks (Treat et al., 2018). More studies of winter CH$_4$ fluxes have been carried out in the boreal biome than in the Arctic biome, but even in the boreal biome, winter CH$_4$ flux measurements remain scarce compared to growing season studies (Viru et al., 2020; Hiyama et al., 2021; Lee et al., 2023). Overall, the limited data available on ABR CH$_4$ fluxes translates into limited knowledge of environmental controls of winter CH$_4$ fluxes. This lack of knowledge is challenging terrestrial biosphere models, often using CH$_4$ emission schemes developed for the growing season or lower latitudes and more temperate environments which can be inaccurate when extrapolated to the ABR carbon cycle (Fisher et al., 2014; Ito et al., 2023).

The goal of this study is to quantify winter CH$_4$ fluxes in different ABR ecosystems and identify environmental controls on fluxes. Our study is based on 660 snowpack diffusion gradient and supporting measurements (snowpack properties, soil temperature and liquid water content) at five different ecosystems in Arctic and boreal biomes in Finland and Canada: a boreal wetland, a closed–crown coniferous boreal forest stand, two open–crown coniferous boreal forest stands, an 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) (Ikonen 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[CH₄]/dz; gC m⁻¹) 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(CH₄); mg C m⁻² day⁻¹) from d[CH₄]/dz (Sommerfeld et al., 1993; Zhu et al., 2014):

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

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

\[ \varphi = 1 - \frac{\rho_{\text{snow}}}{\rho_{\text{ice}}} + \Theta \cdot \left( \frac{\rho_{\text{water}}}{\rho_{\text{ice}}} - 1 \right) \] (2)

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

where \( \rho \) 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 (\( \rho_{\text{ice}} \)) must be adjusted for ice temperature (\( T_{\text{ice}} \)) (Harvey et al., 2017):

\[ \rho_{\text{ice}} = -0.0001 \cdot T_{\text{ice}} + 0.9168 \] (4)
Standard diffusion coefficients of CH$_4$ are available in literature but must be corrected for temperature and pressure (Marrero and Mason, 1972; Massman, 1988):

$$D = 0.1859 \cdot \left(\frac{T}{T_0}\right)^{1.747}$$  \hspace{1cm} (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 CH$_4$ concentration through wind pumping and inducing a negative bias on CH$_4$ 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). CH$_4$ concentration was measured with a Licor LI–7810 CH$_4$/CO$_2$/H$_2$O 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 CH$_4$ calibration gas (Linde Canada, Ottawa, Ontario). The CH$_4$ concentration of gas samples was calculated based on a calibration curve of gas standards ranging from 0 to 10 ppm of CH$_4$. 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 km$^2$. 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 CH$_4$ 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 cm$^3$ snow cutters; $\sigma(\rho_{snow}) \approx 9\%$; 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 CH$_4$ 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 $-0.21$ mg C m$^{-2}$ day$^{-1}$ (CH$_4$ uptake) to $0.33$ mg C m$^{-2}$ day$^{-1}$ (CH$_4$ emissions) with a mean rate of $0.03 \pm 0.08$ mg C m$^{-2}$ day$^{-1}$ (mean ± standard deviation), except for a few hotspots at CB that emitted CH$_4$ up to $1.46$ mg C m$^{-2}$ day$^{-1}$ with a mean rate of $0.78 \pm 0.31$ mg C m$^{-2}$ 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 $-0.43 \pm 0.34$ mg C m$^{-2}$ day$^{-1}$ (MM) and $-0.47 \pm 0.26$ mg C m$^{-2}$ day$^{-1}$ (SOF–for). The SOD–wet boreal wetland displayed high CH$_4$ emissions throughout winter, with rates up to $48.51$ mg C m$^{-2}$ day$^{-1}$ and an average of $4.57 \pm 7.34$ mg C m$^{-2}$ day$^{-1}$. The boreal wetland F$_{CH4}$ 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$_{CH4}$ 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$_{CH4} > Q3 + 1.5$ IQR where Q3 is the third quartile and IQR the interquartile range. The F$_{CH4}$ from the boreal wetland is shown on a separate axis since the range of F$_{CH4}$ 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$_{CH4}$ 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$_{CH4}$ and soil LWC (Fig. 2). The correlation between F$_{CH4}$ 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.
**Discussion**

CH$_4$ flux regimes were previously observed mostly during the growing season, whereas our study focused on winter CH$_4$ fluxes. Our findings support the prevailing notion of boreal forest upland soils generally acting as CH$_4$ sinks (Lai, 2009; Lee et al., 2023) and wetlands acting as CH$_4$ sources (Oertel et al., 2016), and that these patterns hold true for the winter period. The winter CH$_4$ 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 CH$_4$ fluxes, whether as CH$_4$ 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 CH$_4$ emission hotspots in Arctic tundra wetlands during winter that emitted on average about 26 times more CH$_4$ than the average of other sample locations (0.78 vs. 0.03 mg C m$^{-2}$ day$^{-1}$). All those CH$_4$ 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 CH$_4$ emission hotspots ($F_{CH4} \geq 0.35$ mg C m$^{-2}$ day$^{-1}$); only 37.5% of wetland sampling locations exhibited high CH$_4$ emissions. Although we did not determine spatially integrated flux estimates for our sites, these hotspots may dominate the winter CH$_4$ flux budget.
Our results do not show a strong correlation between winter CH$_4$ fluxes and T$_{soil}$ or snow parameters, unlike some previous studies that have found a correlation between CH$_4$ 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 CH$_4$ fluxes, but that deeper T$_{soil}$ could have a stronger correlation since most CH$_4$ 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 CH$_4$ fluxes in ABR, several terrestrial biosphere models would have to reassess how CH$_4$ fluxes are estimated as most use T$_{soil}$ or T$_{air}$ as a main control of CH$_4$ flux computation. However, it is also possible that other factors are masking the temperature dependency of winter CH$_4$ 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 CH$_4$ sinks of forested regions which might be why the rate of CH$_4$ 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 CH$_4$ uptake with higher soil carbon substrate availability or soil microbial activity as discovered recently for growing season CH$_4$ uptake (Voigt et al. 2023). The slower diffusion of CH$_4$ 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 CH$_4$ fluxes assuming again that an important fraction of CH$_4$ 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 CH$_4$ 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 CH$_4$ 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 CH$_4$ 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 CO$_2$ 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 CH$_4$ 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, CH$_4$ 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 CH$_4$ production is higher than what is released into the atmosphere, at least for this part of winter. The trapped CH$_4$ is probably released during ice melt, which is coherent with previous studies that showed bursts of CH$_4$ 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 CH$_4$ production.
The shoulder seasons (i.e., autumn freeze and spring thaw) are important periods of change in CH$_4$ exchange regimes with an important contribution to the annual CH$_4$ 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 CH$_4$ 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 CH$_4$ 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 CH$_4$ 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 CH$_4$ 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 CH$_4$ fluxes and highlights the importance of an integrative view of CH$_4$ fluxes and soil properties.

5 Conclusions

We measured in situ winter CH$_4$ 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 CH$_4$ uptake from the atmosphere, but the rate of CH$_4$ 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 CH$_4$ 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 CH$_4$ 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 CH$_4$ fluxes. Our study stresses the importance of considering ABR winter CH$_4$ 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:


References


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 (≤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).

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

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).

<table>
<thead>
<tr>
<th>Site</th>
<th>Ecosystem</th>
<th>Dominant species</th>
<th>Acronym</th>
<th>Soil layers</th>
<th>Mean Annual Tₘ</th>
<th>Annual Precipitation</th>
<th>Growing Season Length</th>
<th>Permafrost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cambridge Bay</td>
<td>Prostrate tundra shrubs</td>
<td>Lichen and moss</td>
<td>CB-mes</td>
<td>Mesic: 0-5 cm organic over dry mineral</td>
<td>-12.5 °C</td>
<td>152 mm</td>
<td>94 days</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wetland: 10-20 cm organic over wet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mineral (clay)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trail Valley Creek</td>
<td>Erect tundra shrubs</td>
<td>Schurb, lichen, moss and</td>
<td>TVC</td>
<td>30-60 cm organic (peat) over mineral</td>
<td>-7.8 °C</td>
<td>175 mm</td>
<td>111 days</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tussock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Havikpak Creek</td>
<td>Open-crown coniferous</td>
<td>Black spruce</td>
<td>HPC</td>
<td>5-50 cm organic (peat) over mineral</td>
<td>-6.6 °C</td>
<td>198 mm</td>
<td>113 days</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>boreal forest</td>
<td></td>
<td></td>
<td>(silty clay)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Montmorency Forest</td>
<td>Closed-crown coniferous</td>
<td>Balsam fir</td>
<td>MM</td>
<td>4-7 cm litter over 7-13 cm organic</td>
<td>2.0 °C</td>
<td>1293 mm</td>
<td>171 days</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td>boreal forest</td>
<td></td>
<td></td>
<td>over wet mineral (sandy loam)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodankylä</td>
<td>Closed-crown coniferous</td>
<td>Scots pine</td>
<td>SOD-for</td>
<td>0.5 cm organic over dry mineral (sand)</td>
<td>1.5 °C</td>
<td>507 mm</td>
<td>168 days</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td>boreal forest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open wetland</td>
<td>Fen and bog</td>
<td>SOD-wet</td>
<td>&gt; 120 cm organic (peatland)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CH₄ flux uncertainty assessment

Sources of uncertainties for FCH₄ can be subdivided into four categories: gas concentration estimates, gas transfer/transport/storage, snow properties estimates and d[CH₄]/dz estimates. The uncertainty on [CH₄] was evaluated from the gas analyzer precision as assessed by the manufacturer. [CH₄] uncertainty was further tested using calibration gases. The gas transfer, transport and storage protocols were tested using calibration gases. The d[CH₄]/dz linear regression uncertainties were evaluated using the standard deviation from the Pearson correlation coefficient \((\sigma = \sqrt{(1 - R^2)/(N - 1)}; \text{Bowley, 1928})\). FCH₄ uncertainty was calculated by uncertainty propagation from d[CH₄]/dz and snow density uncertainties.

The FCH₄ uncertainty assessment showed that the two main sources of uncertainty are associated with snow density measurements (\(\sigma(\rho_{\text{snow}}) \approx 9%\); Proksch et al., 2016) and with d[CH₄]/dz (mean \(R^2 = 0.901 (\sigma = 0.135)\) for FCH₄ \(\geq 0.05 \ \text{mg C m}^{-2} \ \text{day}^{-1}; N = 339\) (Table S1). The mean FCH₄ 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. FCH₄ uncertainty sources. [CH₄] precision was evaluated at a concentration of 2 ppm.

<table>
<thead>
<tr>
<th>FCH₄ uncertainty source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>[CH₄] estimate</td>
<td></td>
</tr>
<tr>
<td>· LI-7810 precision</td>
<td>0.6 ppm (0.03%)</td>
</tr>
<tr>
<td>· Measurement stability</td>
<td>0.001 ppm (0.05%; N=169)</td>
</tr>
<tr>
<td>· Reference gas</td>
<td>0.018 ppm (1%)</td>
</tr>
<tr>
<td>· Calibration fit</td>
<td>0.005 ppm (0.25%; N=8; (\sigma = 0.067%))</td>
</tr>
<tr>
<td>· Transfer, transport and storage test</td>
<td>0.012 ppm (0.63%; N=5)</td>
</tr>
</tbody>
</table>

Snow density (kg·m⁻³) 9%

| d[CH₄]/dz linear regression (gC·m⁻³) | 17.66% (N=339; \(\sigma = 17.14\%\)) |

Figure S2. FCH₄ uncertainty relationship to \(|F_{\text{CH₄}}|\) 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:

\[
LWC = a \cdot \frac{\rho_b}{\rho_w} \cdot |T_{soil}|^{-b}
\]

\[
\ln a = 0.5519 \cdot \ln SSA + 0.2618 ; \ln b = -0.264 \cdot \ln SSA + 0.3711
\]

where \(\rho_w\) and \(\rho_b\) (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).

\[
SAA = 3.89 \cdot d_g^{-0.905}
\]

\[
\ln d_g = f_c \cdot \ln M_c + f_{si} \cdot \ln M_{si} + f_{sa} \cdot \ln M_{sa}
\]

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).
CH$_4$ flux across vegetation types at Trail Valley Creek

![Diagram showing CH$_4$ flux across different vegetation types with bars representing different years.]

**Figure S3.** CH$_4$ flux across vegetation types at Trail Valley Creek. Vegetation types were not distinguished by soil moisture classes (like at the Cambridge Bay study site) since the information was not available at the scale of the sampling locations.
Spatial variability of boreal wetland CH$_4$ fluxes

Figure S4. CH$_4$ flux spatial variability in the boreal wetland at the Sodankylä study site (SOD–wet).
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 FCO₂ > Q₃ + 1.5 IQR where Q₃ is the third quartile and IQR the interquartile range.
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.
Abstract

Unprecedented warming of Arctic–boreal regions (ABR) has poorly understood consequences on carbon cycle processes. Uncertainties in annual methane (CH$_4$) budgets partly arise because of limited data availability during winter. In this study, winter CH$_4$ flux measurements were conducted using the snowpack diffusion gradient method over five ABR ecosystem types in Canada and Finland: closed–crown and open–crown coniferous boreal forest, boreal wetland and erect–shrub and prostrate–shrub tundra. Boreal forest uplands acted as net CH$_4$ sinks, while the boreal wetland acted as net CH$_4$ source during winter. We identified several wetland tundra CH$_4$ emission hotspots and large spatial variability in boreal wetland CH$_4$ emissions. In the boreal forest uplands, soil liquid water content was identified as an important environmental control of winter CH$_4$ fluxes. Our results indicate non–negligible winter CH$_4$ flux, which must be accounted for in annual carbon balance and terrestrial biosphere models over ABR.

Plain Language Summary

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

1 Introduction

Methane (CH$_4$) exchange between the ground surface and the atmosphere in Arctic and boreal biomes (hereafter called Arctic–boreal regions; ABR) play an important role in the global climate with potentially important responses to a warming climate (Bekryaev et al., 2010; Kirschke et al., 2013; Yvon–Durocher et al., 2014; Schuur et al., 2015; Dean et al., 2018; Rößger et al., 2022). The response of ABR CH$_4$ fluxes to temperature is especially relevant since the ABR are warming up to four times faster than the rest of the planet (Derksen et al., 2019; Rantanen et al., 2022). The soils of ABR store a vast amount of labile organic matter due to inherently slow decomposition rates, largely attributable to cold temperatures (Tarnocai et al., 2009; Deluca and Boisvenue, 2012; Ravn et al., 2020). Therefore, altered CH$_4$ exchange rates due to ABR warming up could generate potentially non–negligible, positive feedback to the global climate system (Natali et al., 2021; Rößger et al., 2022; Schuur et al., 2022). Poor understanding of environmental controls on CH$_4$ exchange during winter constitutes a large source of uncertainty in the ABR CH$_4$ budget (McGuire et al., 2012; Mastepanov et al., 2013; Treat et al., 2018).
The net soil CH$_4$ flux is a result of three groups of processes: production, oxidation, and transport of CH$_4$. CH$_4$ in soils is produced by methanogens during organic matter decomposition under mostly anoxic conditions, which typically occur in deeper soil layers or in water–saturated environments (Zhang et al., 2017; Feng et al., 2020; Bastviken et al., 2023). In contrast, under predominantly aerobic conditions, CH$_4$ is oxidized by methanotrophs as a source of energy and carbon (Lai, 2009; Bastviken et al., 2023). Such aerobic conditions are often found in drier upper soil layers in mineral upland soils. In well–drained soils, CH$_4$ oxidation typically exceeds production resulting in a net soil CH$_4$ sink that removes CH$_4$ from the atmosphere (Lai, 2009; Lee et al., 2023). In contrast, CH$_4$ oxidation in wetlands is lower than production resulting in net CH$_4$ emissions (Topp and Pattey, 1997; Roslev et al., 1997). Still, CH$_4$ oxidation in wetlands is an important process that removes a large percentage of CH$_4$ produced in saturated soil layers before it can reach the atmosphere (Oertel et al., 2016). During the oxidation process, CH$_4$ is oxidized to carbon dioxide (CO$_2$) and water (H$_2$O). Methane transport, i.e., the movement of CH$_4$ from its zone of production to the atmosphere by diffusion, ebullition, and plant–mediated transport also plays an important role in mitigating CH$_4$ oxidation by limiting the time during which methanotrophs can consume CH$_4$ (Bastviken et al., 2023). The vegetation composition of the ecosystem has been shown to impact CH$_4$ fluxes by providing the organic matter substrate for CH$_4$ production, bypassing zones of CH$_4$ oxidation by plant–mediated transport, and by its indirect impact on water table and thaw depth (King et al., 1998; Andresen et al., 2017; Bastviken et al., 2023).

The majority of prior CH$_4$ studies in the ABR has focused on snow–free growing season fluxes (e.g., Ullah et al., 2009; Zona et al., 2009; Helbig et al., 2016; Kuhn et al., 2021). The largest CH$_4$ flux measurement network, FLUXNET–CH$_4$, provides limited winter data from ABR due to the failure of equipment in cold harsh conditions (Knox et al., 2019; Delwiche et al., 2021). The few studies on winter CH$_4$ fluxes in the Arctic biome that exist showed that winter can contribute up to 40 to 50% of the annual net CH$_4$ emissions (Zona et al., 2016; Treat et al., 2018; Rößger et al., 2022; Ito et al., 2023). The length of winter typically increases with latitude and can span the period from September to June. Most of the winter ABR CH$_4$ studies focus on wetlands and peatlands where higher emissions are expected, with little attention to CH$_4$ sinks (Treat et al., 2018). More studies of winter CH$_4$ fluxes have been carried out in the boreal biome than in the Arctic biome, but even in the boreal biome, winter CH$_4$ flux measurements remain scarce compared to growing season studies (Viru et al., 2020; Hiyama et al., 2021; Lee et al., 2023). Overall, the limited data available on ABR CH$_4$ fluxes translates into limited knowledge of environmental controls of winter CH$_4$ fluxes. This lack of knowledge is challenging terrestrial biosphere models, often using CH$_4$ emission schemes developed for the growing season or lower latitudes and more temperate environments which can be inaccurate when extrapolated to the ABR carbon cycle (Fisher et al., 2014; Ito et al., 2023).

The goal of this study is to quantify winter CH$_4$ fluxes in different ABR ecosystems and identify environmental controls on fluxes. Our study is based on 660 snowpack diffusion gradient and supporting measurements (snowpack properties, soil temperature and liquid water content) at five different ecosystems in Arctic and boreal biomes in Finland and Canada: a boreal wetland, a closed–crown coniferous boreal forest stand, two open–crown coniferous boreal forest stands, an 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) (Ikonen 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[CH₄]/dz; gC m⁻¹) 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 (FCH₄; mg C m⁻² day⁻¹) from d[CH₄]/dz (Sommerfeld et al., 1993; Zhu et al., 2014):

\[ F_{CH₄} = -\phi \cdot \tau \cdot D \cdot \frac{d[CH₄]}{dz} \]  

(1)

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

\[ \phi = 1 - \frac{\rho_{snow}}{\rho_{ice}} + \Theta \cdot \left( \frac{\rho_{water}}{\rho_{ice}} - 1 \right) \]  

(2)

\[ \tau = \frac{1-(1-\phi)^{2/3}}{\phi} \approx \phi^{1/3} \]  

(3)

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

\[ \rho_{ice} = -0.0001 \cdot T_{ice} + 0.9168 \]  

(4)
Standard diffusion coefficients of CH₄ are available in literature but must be corrected for temperature and pressure (Marrero and Mason, 1972; Massman, 1988):

$$D = 0.1859 \cdot \left(\frac{T}{T_0}\right)^{1.747}$$  \hspace{1cm} (5)

where $T$ is the air temperature and $T_0$ 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., $F_{\text{CH}_4}$ overestimation; Seok et al., 2009). Such layers were rarely found in our study sites and did not cause the $d[\text{CH}_4]/dz$ 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, $d[\text{CH}_4]/dz$ was not measured in days following a strong wind event. Monitoring of $F_{\text{CH}_4}$ at a few sampling locations did not show any relationship between $F_{\text{CH}_4}$ and wind speed or atmospheric pressure (Mavrovic et al., 2023).

### 2.3 Data collection

The $d[\text{CH}_4]/dz$ 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 ($T_{\text{soil}}$) was measured at 1 cm depth below the soil–snow interface, and three measurements within 1 m of $T_{\text{soil}}$ 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 CH₄ emissions in tundra sites (CB and TVC) and open–crown boreal forest (HCP). At those sites, fluxes ranged from −0.21 mg C m⁻² day⁻¹ (CH₄ uptake) to 0.33 mg C m⁻² day⁻¹ (CH₄ emissions) with a mean rate of 0.03 ± 0.08 mg C m⁻² day⁻¹ (mean ± standard deviation), except for a few hotspots at CB that emitted CH₄ up to 1.46 mg C m⁻² day⁻¹ with a mean rate of 0.78 ± 0.31 mg C m⁻² day⁻¹ (Fig. 1). The winter CH₄ hotspots were revisited 10 times over a period of 8 weeks and consistently displayed high CH₄ emissions.

Several vegetation types were found in the Arctic tundra sites of CB and TVC. The main differences between CH₄ 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 CH₄ 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 CH₄ 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 CH₄ uptake rates throughout winter of −0.43 ± 0.34 mg C m⁻² day⁻¹ (MM) and −0.47 ± 0.26 mg C m⁻² day⁻¹ (SOF–for). The SOD–wet boreal wetland displayed high CH₄ emissions throughout winter, with rates up to 48.51 mg C m⁻² day⁻¹ and an average of 4.57 ± 7.34 mg C m⁻² day⁻¹. The boreal wetland F_CH₄ 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_CH₄ with some sampling locations emitting CH₄ at average rates up to 50 times higher than the lowest ones (Fig. S4).

**Figure 1.** CH₄ flux across the study sites. Outliers were defined as F_CH₄ > Q₃ + 1.5 IQR where Q₃ is the third quartile and IQR the interquartile range. The F_CH₄ from the boreal wetland is shown on a separate axis since the range of F_CH₄ 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_CH4 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_CH4 and soil LWC (Fig. 2). The correlation between F_CH4 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. CH$_4$ 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

CH$_4$ flux regimes were previously observed mostly during the growing season, whereas our study focused on winter CH$_4$ fluxes. Our findings support the prevailing notion of boreal forest upland soils generally acting as CH$_4$ sinks (Lai, 2009; Lee et al., 2023) and wetlands acting as CH$_4$ sources (Oertel et al., 2016), and that these patterns hold true for the winter period. The winter CH$_4$ 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 CH$_4$ fluxes, whether as CH$_4$ 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 CH$_4$ emission hotspots in Arctic tundra wetlands during winter that emitted on average about 26 times more CH$_4$ than the average of other sample locations (0.78 vs. 0.03 mg C m$^{-2}$ day$^{-1}$). All those CH$_4$ 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 CH$_4$ emission hotspots ($F_{CH_4} \geq 0.35$ mg C m$^{-2}$ day$^{-1}$); only 37.5% of wetland sampling locations exhibited high CH$_4$ emissions. Although we did not determine spatially integrated flux estimates for our sites, these hotspots may dominate the winter CH$_4$ flux budget.
Our results do not show a strong correlation between winter CH$_4$ fluxes and T$_{soil}$ or snow parameters, unlike some previous studies that have found a correlation between CH$_4$ 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 CH$_4$ fluxes, but that deeper T$_{soil}$ could have a stronger correlation since most CH$_4$ 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 CH$_4$ fluxes in ABR, several terrestrial biosphere models would have to reassess how CH$_4$ fluxes are estimated as most use T$_{soil}$ or T$_{air}$ as a main control of CH$_4$ flux computation. However, it is also possible that other factors are masking the temperature dependency of winter CH$_4$ 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 CH$_4$ sinks of forested regions which might be why the rate of CH$_4$ 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 CH$_4$ uptake with higher soil carbon substrate availability or soil microbial activity as discovered recently for growing season CH$_4$ uptake (Voigt et al. 2023). The slower diffusion of CH$_4$ 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 CH$_4$ fluxes assuming again that an important fraction of CH$_4$ 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 CH$_4$ 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 CH$_4$ 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 CH$_4$ 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 CO$_2$ 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 CH$_4$ 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, CH$_4$ 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 CH$_4$ production is higher than what is released into the atmosphere, at least for this part of winter. The trapped CH$_4$ is probably released during ice melt, which is coherent with previous studies that showed bursts of CH$_4$ 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 CH$_4$ 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 FCH4, which must be accounted for in annual carbon balance and terrestrial biosphere models over ABR. Although FCH4 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.

Acknowledgment

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**Open Research**

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


**References**


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 (≤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).

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

**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).

<table>
<thead>
<tr>
<th>Site</th>
<th>Ecosystem</th>
<th>Dominant species</th>
<th>Acronym</th>
<th>Soil layers</th>
<th>Mean Annual Tₘ</th>
<th>Annual Precipitation</th>
<th>Growing Season Length</th>
<th>Permafrost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cambridge Bay</td>
<td>Prostrate tundra shrubs</td>
<td>Lichen and moss</td>
<td>CB-mes</td>
<td>Mesic: 0-5 cm organic over dry mineral</td>
<td>-12.5 °C</td>
<td>152 mm</td>
<td>94 days</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Open wetland</td>
<td>Sedge fen</td>
<td>CB-wet</td>
<td>Wetland: 10-20 cm organic over wet mineral (clay)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trail Valley Creek</td>
<td>Erect tundra shrubs</td>
<td>Schurb, lichen, moss and tussock</td>
<td>TVC</td>
<td>30-60 cm organic (peat) over mineral</td>
<td>-7.8 °C</td>
<td>175 mm</td>
<td>111 days</td>
<td>Continuous</td>
</tr>
<tr>
<td>Havikpak Creek</td>
<td>Open-crown coniferous boreal forest</td>
<td>Black spruce</td>
<td>HPC</td>
<td>5-50 cm organic (peat) over mineral (silty clay)</td>
<td>-6.6 °C</td>
<td>198 mm</td>
<td>113 days</td>
<td>Continuous</td>
</tr>
<tr>
<td>Montmorency Forest</td>
<td>Closed-crown coniferous boreal forest</td>
<td>Balsam fir</td>
<td>MM</td>
<td>4-7 cm litter over 7-13 cm organic over wet mineral (sandy loam)</td>
<td>2.0 °C</td>
<td>1293 mm</td>
<td>171 days</td>
<td>Absent</td>
</tr>
<tr>
<td>Sodankylä</td>
<td>Closed-crown coniferous boreal forest</td>
<td>Scots pine</td>
<td>SOD-for</td>
<td>0.5 cm organic over dry mineral (sand)</td>
<td>1.5 °C</td>
<td>507 mm</td>
<td>168 days</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td>Open wetland</td>
<td>Fen and bog</td>
<td>SOD-wet</td>
<td>&gt; 120 cm organic (peatland)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CH₄ flux uncertainty assessment

Sources of uncertainties for F_CH₄ can be subdivided into four categories: gas concentration estimates, gas transfer/transport/storage, snow properties estimates and d[CH₄]/dz estimates. The uncertainty on [CH₄] was evaluated from the gas analyzer precision as assessed by the manufacturer. [CH₄] uncertainty was further tested using calibration gases. The gas transfer, transport and storage protocols were tested using calibration gases. The d[CH₄]/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_CH₄ uncertainty was calculated by uncertainty propagation from d[CH₄]/dz and snow density uncertainties.

The F_CH₄ uncertainty assessment showed that the two main sources of uncertainty are associated with snow density measurements ($\sigma(\rho_{\text{snow}}) \approx 9\%$; Proksch et al., 2016) and with d[CH₄]/dz (mean $R^2 = 0.901$ ($\sigma = 0.135$) for F_CH₄ ≥ 0.05 mg C m⁻² day⁻¹; N = 339) (Table S1). The mean F_CH₄ 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_CH₄ uncertainty sources. [CH₄] precision was evaluated at a concentration of 2 ppm.

<table>
<thead>
<tr>
<th>F_CH₄ uncertainty source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>[CH₄] estimate</td>
<td></td>
</tr>
<tr>
<td>· LI-7810 precision</td>
<td>0.6 ppm (0.03%)</td>
</tr>
<tr>
<td>· Measurement stability</td>
<td>0.001 ppm (0.05%; N=169)</td>
</tr>
<tr>
<td>· Reference gas</td>
<td>0.018 ppm (1%)</td>
</tr>
<tr>
<td>· Calibration fit</td>
<td>0.005 ppm (0.25%; N=8; $\sigma = 0.067%$)</td>
</tr>
<tr>
<td>· Transfer, transport and storage test</td>
<td>0.012 ppm (0.63%; N=5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Snow density (kg·m⁻³)</th>
<th>9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>d[CH₄]/dz linear regression (gC·m⁻⁴)</td>
<td>17.66% (N=339; $\sigma = 17.14%$)</td>
</tr>
</tbody>
</table>

**Figure S2.** F_CH₄ uncertainty relationship to |F_CH₄| 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:

\[ LWＣ = a \cdot \frac{\rho_b}{\rho_w} \cdot |T_{soil}|^{-b} \]  
\[ \ln a = 0.5519 \cdot \ln SSA + 0.2618 \; ; \; \ln b = -0.264 \cdot \ln SSA + 0.3711 \]  

where \( \rho_w \) and \( \rho_b \) (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).

\[ SＡＡ = 3.89 \cdot d_g^{−0.905} \]  
\[ \ln d_g = f_c \cdot \ln M_c + f_{si} \cdot \ln M_{si} + f_{sa} \cdot \ln M_{sa} \]

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).
**CH$_4$ flux across vegetation types at Trail Valley Creek**

![Figure S3](chart.png)

**Figure S3.** CH$_4$ flux across vegetation types at Trail Valley Creek. Vegetation types were not distinguished by soil moisture classes (like at the Cambridge Bay study site) since the information was not available at the scale of the sampling locations.
Spatial variability of boreal wetland CH$_4$ fluxes

**Figure S4.** CH$_4$ flux spatial variability in the boreal wetland at the Sodankylä study site (SOD–wet).
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_{CO₂} > Q₃ + 1.5 IQR where Q₃ is the third quartile and IQR the interquartile range.