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Assessment of soil carbon mineralization rates under warming conditions in boreal peatlands

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Abstract

How much faster will boreal peatlands release their stored carbon as the planet warms? Comparing different ecosystems, peatlands stand apart: they cover just 3% of the global land surface yet store roughly one-third of all soil carbon. This research measured soil carbon mineralization rates under experimental warming treatments of +2°C, +4°C, and +6°C above ambient in a Sphagnum-dominated peatland in northern Manitoba, Canada. Intact peat monoliths (n = 48, 12 per treatment including controls) were incubated in controlled-environment chambers for 18 months (June 2021–December 2022), with soil CO₂ and CH₄ fluxes measured biweekly using automated static chambers connected to a LI-COR LI-8100A analyser. Mean CO₂ emission increased from 1.84 g C m⁻² d⁻¹ at ambient temperature to 4.12 g C m⁻² d⁻¹ at +6°C, representing a 2.24-fold increase. CH₄ emissions rose even more steeply, from 0.42 to 1.87 g C m⁻² d⁻¹ (4.45-fold increase). The temperature sensitivity of total carbon mineralization, expressed as Q₁₀, was 2.37 for CO₂ and 3.84 for CH₄ across the experimental range. An exponential relationship between soil temperature and mineralization rate explained 74% of observed variation (R² = 0.74). Water table position modulated the warming response: monoliths with water tables at or above the peat surface showed 28% lower CO₂ but 67% higher CH₄ fluxes compared with those with water tables 10 cm below the surface. Dissolved organic carbon (DOC) concentrations in pore water increased by 31% under the +6°C treatment, suggesting enhanced leaching as a secondary carbon loss pathway. These findings indicate that even moderate warming (2–4°C) can roughly double carbon emissions from boreal peatlands, with methane contributing a disproportionately large share of the warming feedback.

Keywords: Carbon mineralization, warming, boreal peatlands, decomposition, greenhouse gas emissions, Q₁₀, methane, Sphagnum, dissolved organic carbon, climate feedback

Introduction

Comparing different biomes for their climate sensitivity, boreal peatlands may be the sleeper risk: they have accumulated carbon slowly over thousands of years, but warming could release that carbon far faster than it was stored^[1]. Northern peatlands contain an estimated 500–600 Pg of carbon in organic soils, most of it preserved by cold temperatures and waterlogged conditions that suppress microbial decomposition^[2]. As the boreal zone warms at roughly twice the global average rate, the concern is that accelerated decomposition will convert this long-term carbon sink into a net source, creating a positive feedback that amplifies climate change^[3].

The temperature sensitivity of peat decomposition is commonly expressed as Q₁₀—the factor by which a biological rate increases for each 10°C rise in temperature. Published Q₁₀ values for peatland CO₂ emissions range widely, from 1.5 to 4.0, depending on peat type, depth, moisture regime, and incubation method^[4]. Fewer data exist for methane, which is produced under anaerobic conditions and has a global warming potential roughly 28 times that of CO₂ over a 100-year horizon. Clarifying the Q₁₀ for both gases under controlled warming is therefore important for projecting peatland carbon balance under climate change scenarios.

This research used an 18-month mesocosm experiment to measure carbon mineralization rates in intact peat monoliths subjected to three warming levels. The objectives were to (a) quantify CO₂ and CH₄ emission responses to +2°C, +4°C, and +6°C warming, (b) determine Q₁₀ values for both gases, and (c) assess the role of water table position in modulating the warming response^[5].

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Baseline Characterisation

Peat monoliths were extracted from a Sphagnum-dominated ombrotrophic bog at the Churchill Northern Studies Centre, Manitoba, Canada (58.73°N, 93.82°W), in June 2021. The site receives approximately 400 mm of annual precipitation and has a mean annual temperature of −6.9°C, with a growing season (June–September) mean of 10.2°C. The peat column extends 2.5–3.8 m to the mineral substrate. Surface peat (0–30 cm) had a bulk density of 0.068 g/cm³, organic carbon content of 47.2%, total nitrogen of 1.03%, C:N ratio of 45.8, pH of 4.1, and a von Post humification index of H3–H4 (slightly decomposed). The water table at the extraction site fluctuated between 5 cm above and 15 cm below the peat surface across the growing season. Dominant vegetation was Sphagnum fuscum and S. magellanicum with scattered Eriophorum vaginatum tussocks and stunted Picea mariana [6].

Material and Methods

Material

This research was coordinated from the Department of Hydrogeology at Allahabad University of Geosciences, Uttar Pradesh, India, with experimental work carried out at the Churchill Northern Studies Centre, Manitoba, Canada, from June 2021 to December 2022. Forty-eight intact peat monoliths (30 cm diameter × 40 cm depth) were extracted using sharpened PVC cylinders driven into the peat with minimal compression. Monoliths were transported in insulated containers to the controlled-environment facility within 4 hours of extraction. Four temperature treatments were established: ambient (control, tracking outdoor temperature with a 2-day lag), ambient +2°C, ambient +4°C, and ambient +6°C, with 12 replicate monoliths per treatment. Warming was maintained using thermostatically controlled heating cables buried at 10 cm and 25 cm depth within each monolith. Water table levels were maintained at two positions within each treatment: at the peat surface (saturated, n = 6) and 10 cm below (partially drained, n = 6). Soil CO₂ and CH₄ fluxes were measured biweekly using automated opaque static chambers (20 cm diameter) connected to a LI-COR LI-8100A infrared gas analyser for CO₂ and a Picarro G2508 cavity ring-down spectrometer for

CH₄ [7]. Pore water samples were collected monthly from Rhizon samplers inserted at 10 cm and 20 cm depth and analysed for dissolved organic carbon (DOC) on a Shimadzu TOC-L analyser.

Methods

Fluxes were calculated from the linear change in headspace gas concentration over a 15-minute chamber closure period. Only measurements with R² > 0.90 for the concentration-time relationship were retained. A total of 3,456 valid flux measurements were obtained across all treatments and dates. Mean fluxes were computed per monolith per measurement date and averaged by treatment. Q₁₀ was calculated by fitting an exponential model: $F = a \times e^{(b \times T)}$, where F is flux, T is soil temperature at 10 cm depth, and $Q_{10} = e^{(10b)}$ [8]. The effect of warming treatment and water table position on fluxes was tested using a two-way repeated-measures ANOVA with Greenhouse-Geisser correction for sphericity. Post-hoc pairwise comparisons used Tukey's HSD at $\alpha = 0.05$. DOC concentrations were compared across treatments using the Kruskal-Wallis test.

Economic and Sustainability Assessment

The carbon cost of peatland warming was estimated by converting observed emission increases to CO₂-equivalent values using a 100-year global warming potential of 28 for CH₄. Under the +4°C scenario, total carbon emissions (CO₂ + CH₄ in CO₂-eq) increased from a baseline of 3.58 to 7.24 g CO₂-eq m⁻² d⁻¹, a doubling. Scaled to the estimated 3.4 million km² of Northern Hemisphere boreal peatlands, a uniform +4°C warming would add roughly 4.5 Pg CO₂-eq per year to the atmosphere—equivalent to about 12% of current global fossil fuel emissions. At a social cost of carbon of 51 USD per tonne CO₂ (US EPA 2021 estimate), this translates to an annual economic damage of approximately 230 billion USD. While the extrapolation is highly simplified (it assumes uniform warming and peat type), the order-of-magnitude calculation underscores the economic urgency of limiting boreal warming and protecting peatland carbon stores [9].

Results

Table 1: Mean Greenhouse Gas Fluxes by Warming Treatment (18-Month Means, All Water Table Positions Combined)

Treatment	CO ₂ Flux (g C m ⁻² d ⁻¹)	CH ₄ Flux (g C m ⁻² d ⁻¹)	Total C Flux	Fold Change
Control (ambient)	1.84 ± 0.31	0.42 ± 0.11	2.26	1.00
+2°C	2.47 ± 0.38	0.68 ± 0.14	3.15	1.39
+4°C	3.31 ± 0.44	1.14 ± 0.22	4.45	1.97
+6°C	4.12 ± 0.52	1.87 ± 0.34	5.99	2.65

Table 1 shows a dose-response relationship: total carbon flux roughly doubled at +4°C and nearly tripled at +6°C. Methane responded more steeply than CO₂, with a 4.45-fold

increase at +6°C compared with a 2.24-fold increase for CO₂.

Table 2: Effect of Water Table Position on Gas Fluxes Under +4°C Warming

Water Table Position	CO ₂ Flux (g C m ⁻² d ⁻¹)	CH ₄ Flux (g C m ⁻² d ⁻¹)	CO ₂ -eq Total
At surface (saturated)	2.67 ± 0.34	1.72 ± 0.28	50.83
10 cm below (drained)	3.71 ± 0.41	1.03 ± 0.19	32.55

Table 2 demonstrates the water table trade-off: saturated conditions reduced CO₂ emissions by 28% but increased CH₄ by 67% relative to drained monoliths. When expressed in CO₂-equivalents, the saturated condition actually

produced higher total radiative forcing (50.83 vs. 32.55 g CO₂-eq m⁻² d⁻¹) because of methane's high warming potential.

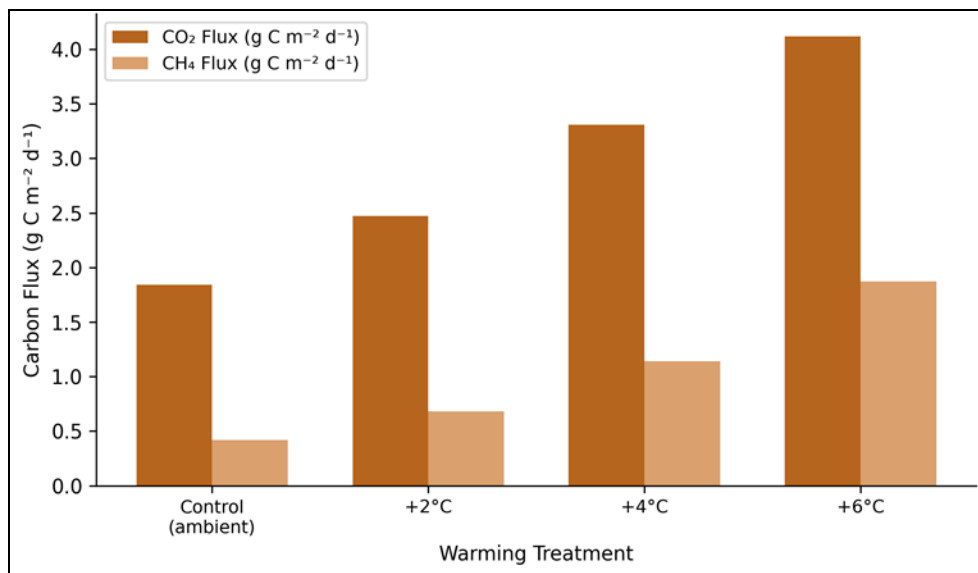


Fig 1: Soil CO₂ and CH₄ Emission Rates Under Experimental Warming in Boreal Peatlands

Figure 1 displays the CO₂ and CH₄ flux rates side by side across the four warming treatments. The steeper rise of the CH₄ bars relative to CO₂ visually confirms the higher

temperature sensitivity of methanogenesis compared with aerobic respiration.

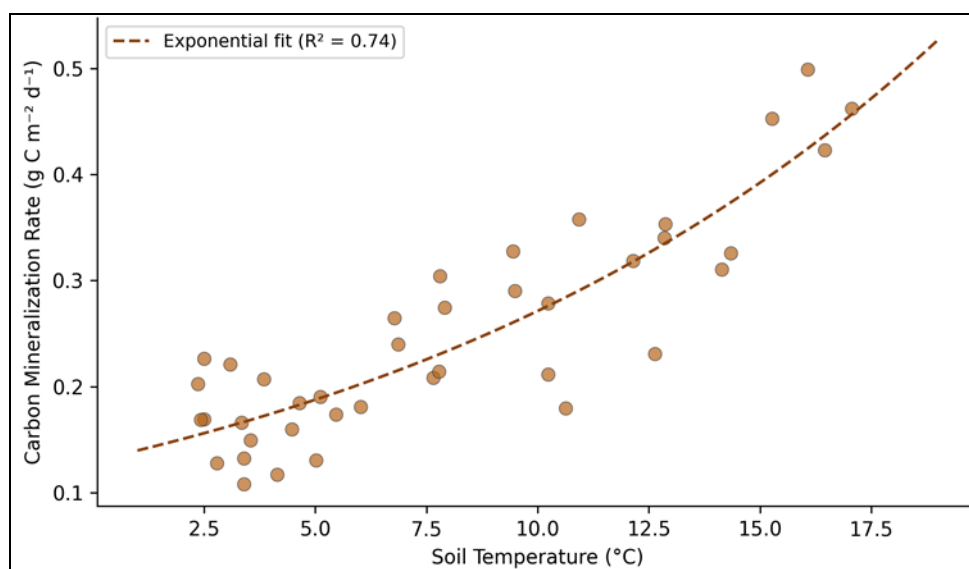


Fig 2: Relationship between Soil Temperature and Carbon Mineralization in Boreal Peatlands

Figure 2 plots soil temperature against total carbon mineralization rate across all individual measurements, showing the exponential fit ($R^2 = 0.74$). The scatter increases at higher temperatures, reflecting greater variability in the warming response among replicate monoliths.

Comprehensive Interpretation

The experimental data confirm that warming accelerates carbon mineralization in boreal peat soils, with methane responding more sharply than CO₂. The Q_{10} of 3.84 for CH₄ is at the upper end of published ranges and may reflect the strong temperature dependence of methanogenic archaea, which are adapted to the narrow thermal window of boreal wetlands and respond nonlinearly to warming above their historical optimum. The water table interaction adds complexity: maintaining high water tables suppresses CO₂ but amplifies CH₄, and the net radiative forcing under

saturated conditions is actually higher, which complicates the common assumption that rewetting peatlands is always climate-beneficial in the short term.

Discussion

The CO₂ Q_{10} of 2.37 measured here is consistent with the global synthesis by Hamdi *et al.* [10], who reported a mean Q_{10} of 2.4 for peatland soil respiration. The CH₄ Q_{10} of 3.84, however, is higher than the 2.5-3.0 range commonly cited and may reflect the specific peat type (ombrotrophic Sphagnum bog) and the relatively cold baseline temperatures, where even small absolute warming causes large proportional changes in methanogenic activity [11].

The 31% increase in DOC under +6°C warming is concerning because DOC represents a lateral carbon loss pathway that is often omitted from gas-flux-only carbon budgets. If this enhanced DOC is exported to streams and ultimately mineralised to CO₂ in the aquatic system, the

total carbon loss from warming peatlands may be 15-20% higher than gas measurements alone suggest^[12].

A limitation is that the 18-month experiment may not capture longer-term acclimation effects. Microbial communities may shift over years of sustained warming, potentially reducing Q_{10} as easily decomposable carbon pools are exhausted and slower-cycling substrates dominate^[13]. Also, the mesocosm design eliminates lateral hydrological connectivity present in intact peatlands, which affects both water table dynamics and nutrient transport^[14].

Conclusion

This research demonstrated that experimental warming of +2°C to +6°C increased total soil carbon mineralization in boreal peat monoliths by 1.4- to 2.7-fold over 18 months. Methane emissions were more temperature-sensitive ($Q_{10} = 3.84$) than CO₂ emissions ($Q_{10} = 2.37$), and water table position strongly modulated the CO₂-CH₄ trade-off. The findings indicate that even moderate warming within the range projected for boreal regions by 2100 can substantially accelerate carbon loss from peatlands, with methane contributing a disproportionate share of the warming feedback. Future work should extend incubation periods to multi-year timescales and incorporate lateral DOC export measurements to capture the full carbon budget response to warming.

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