



Deep winter dissolved organic carbon transfer from taliks in permafrost landscapes

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Supplementary Information

The Supplementary Information includes:

- Materials and Methods
- Supplementary Table S-1
- Supplementary Figures S-1 and S-2
- Supplementary Information References

Materials and Methods

Study sites

Two field campaigns took place near Eight Mile Lake (63°52' N, 149° 15' W; 700 m a.s.l), in Alaska, USA during winter 2024 (February – March) and 2025 (March; Fig. 1). These two field missions, each lasting two weeks, enabled soil pore water and inlet (first-order stream) water collection from the Eight Mile Lake catchment, and river water from the Panguingue Creek catchment (second-order stream). These catchments share similar characteristics, these are moist acidic tundras with an organic layer of 45–65 cm thick (> 20% OC) which covers cryoturbated mineral soil (< 20% OC) that is a mixture of glacial till (small stones and cobbles) and windblown loess, and an active layer thickness between 50 and 120 cm (Kelley *et al.*, 2021; Natali *et al.*, 2011). Their geology is composed of Tertiary sedimentary rocks, overlain by gravelly glacial till and aeolian silt including the Pliocene Nenana gravel (Soil Survey Staff, 1999). The mean annual temperature at the ACCLIMATE observatory was -1.7 ± 13 °C between 2004 and 2023 with a non-summer (October–April) average of -10 ± 10 °C and summer (May–September) average of 9.8 ± 6.2 °C (Celis *et al.*, 2024). The mean annual precipitation (rain and snow) is 378 mm, and the snow cover present from mid-September to mid-May is on average 52 cm thick (Natali *et al.*, 2012; Osterkamp *et al.*, 2009; Vogel *et al.*, 2009). The Eight Mile Lake catchment is characterized by high spatial heterogeneity, including differences in permafrost degradation, thermokarst subsidence, soil geochemistry, and vegetation (Hirst *et al.*, 2023; Mauclet *et al.*, 2023; Monhonval *et al.*, 2023; Villani *et al.*, 2022). Water tracks are present on the Eight Mile Lake catchment and are identifiable on the map (Fig. 1b,c). Water tracks have expanded upslope in the watershed since 1954 (Rodenhizer *et al.*, 2022). With permafrost thaw, water tracks are

often combined with subsidence (Del Vecchio and Evans, 2025). Compared to the surrounding area, water tracks at the study site have deeper permafrost, a thicker superficial organic-rich horizon (Monhonval *et al.*, 2023), and support dense vegetation (Rodenhizer *et al.*, 2022). Ground-penetrating radar surveys at this site show that supra-permafrost taliks are not continuous beneath the hillslope, but are preferentially located within and beneath the water track, where the active layer fails to fully refreeze in winter; surrounding soils outside the water track remain frozen year-round (Henrion *et al.*, 2025). This was corroborated by lateral coring conducted in 2025 at distances of 2–5 m from the center of the water track (cores U2, D2, D3), reaching just beyond its margin, where coring did not intersect any talik, confirming that the unfrozen zone remains spatially confined to the water track.

Air and soil temperatures, and snow depth

The air and soil temperatures were monitored continuously between November 1 and May 15 2023–2024 and 2024–2025 (winter period) using ZL6 Pro Data Logger connected to TEROS-12 (Meter Group) probes with a temporal resolution of one hour. These loggers were installed outside of the water track and upstream of the water track (Fig. 1b), and the soil temperature was monitored in two replicates at 10, 30 and 60 cm depth in each location. Within 2 m diameter around each logger, snow depth was measured in triplicates in February – March 2024 and 2025.

Soil coring and water sampling

At the Eight Mile Lake catchment, five (2024) and six (2025) cores were sampled using a gas-powered auger where snow and talik surface depth were measured. In 2024, all cores were carried out in the main water track of the study site (two upstream U1 and U2 and three downstream D1, D2 and D3 of the water track) and in 2025, three cores were carried out in the main water track (one upstream U2 and two downstream D1 and D3 of the water track) and three cores were carried out outside the water track (O1, O2, and O3, parallel to the main water track). Between 2024 and 2025, three cores (U2, D1 and D3) were sampled at the same place to enable year-on-year comparison. Each core was split between the surface frozen portion of the core within the active layer and the underlying talik portion (Table S-1). The talik depth reaches at least 1 m at all sites in 2024 and 2025: as the organo-mineral transition occurs at 33 ± 11 cm across the study site (Mauclet *et al.*, 2023; Monhonval *et al.*, 2023), taliks extend into both the organic and mineral soil layers. No permafrost was included in the sampling. After thawing frozen portions of the core (< 24 h after sampling) to allow ground ice to melt, macrorhizons with a pore size of $0.15 \mu\text{m}$ and a 10 cm porous part (Rhizosphere, Wageningen, The Netherlands) connected to a 60 mL polypropylene syringe (BD Plastipak luer lock), were inserted in soil sample to collect the soil pore water from the frozen portion of the core and from the talik, resulting in 22 soil pore water samples. In addition to these cores, liquid free-standing water was collected from a shallow unconfined saturated talik zone at the most downstream site in 2024 (at 48 cm depth) and 2025 (at 40 cm depth; D4; Fig. S-1). Within the same soil core, we compared soil pore waters from the frozen portion of the core and from the taliks at the vertical scale, using $\delta^{30}\text{Si}$ to trace the processes that constrain talik connectivity (i.e., closed versus lateral taliks).

Stream waters, at the inlet (first-order stream) and the Panguingue Creek river (second-order stream), were collected in winter 2024 ($n = 1$ for the inlet, and $n = 1$ for the Panguingue Creek river) and winter 2025 ($n = 1$ for the inlet and $n = 1$ for the Panguingue Creek river) at the same position under the ice (38 cm thick at the inlet; 90 cm thick in 2024 and 68 cm thick in 2025 for the Panguingue Creek river) using an ice auger, resulting in 6 stream water samples.

Chemical analyses

pH and conductivity measurements

In soil pore waters ($n = 22$), pH and specific electrical conductivity (“conductivity” in the text; measured at 25°C) were measured in the laboratory (UCLouvain, Belgium) within one week using a SevenCompact™ Duo S213 probe in a clean room. In stream waters ($n = 4$), the pH and electrical conductivity ($\mu\text{S cm}^{-1}$) were directly measured on the field using a probe from HANNA Instruments (HI991300). pH and conductivity are reported throughout as general background parameters.

Water isotopes measurements

In stream waters ($n = 4$, Fig. S-2), the water isotopes ($\delta^{18}\text{O}$ and δD) values were determined on unfiltered water using Cavity Ring-Down Spectroscopy on a Liquid Water Isotope Analyzer (L2130-i, Picarro®, Earth and Life Institute, UCLouvain, Belgium). Values are normalized between SLAP and VSMOW and reported in per mil deviation relative to VSMOW. Three reference materials were used: USGS46, USGS47 and USGS48. The reproducibility is $> 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $> 0.6\text{‰}$ for δD .

Dissolved organic carbon concentration measurements

In stream waters and soil pore waters ($n = 26$), the concentration in dissolved organic carbon (DOC) was measured using high-temperature catalytic oxidation (Shimadzu® TOC-VCPH) with a detection limit of 0.1 mg L^{-1} and an accuracy of $\pm 2\%$.

Radiocarbon analysis

In stream waters ($n = 4$) and the talik pore waters with enough volume (U2, D1-D4; $n = 5$), the radiocarbon signature of the DOC was analyzed at the Arizona Climate and Ecosystems (ACE) Isotope Laboratory (Northern Arizona University) following the published method (Lang *et al.*, 2016). Briefly, to determine the radiocarbon signature of DOC, samples underwent wet chemical oxidation to convert them to CO_2 , which was analyzed on a Miniaturized Carbon Dating System (MICADAS) with a carbonate handling system (CHS2) and gas interface system (GIS). DOC radiocarbon measurements were calibrated using gaseous OX-II and radiocarbon-dead C dioxide (IonPlus, Switzerland). A standard deviation of 8‰ and a blank radiocarbon age of 38,000 years are spec. Within our analyses, OX- II replicates had a standard deviation of 7.4‰ . Samples were blank subtracted using the chemical glycine standard with an average radiocarbon age of $30,760 \pm 4701$ years ($n = 7$). Additionally, a replicate of a known environmental DOC sample was run on each day of analysis to assess instrument performance. Across two replicates representing the two days of analysis, the standard deviation of this internal standard was 3‰ . Radiocarbon ages are reported in years BP (Before Present, where present = 1950). The radiocarbon value reported for 2024 for the second order stream (Panguingue Creek) is from Roux *et al.* (2026) following the same protocol.

Dissolved gas concentrations (CO_2 and CH_4)

In stream waters ($n = 4$) and free-standing water from D4 ($n = 2$), the concentrations in dissolved CO_2 and CH_4 were analyzed. A syringe was filled with 30 ml of water and 30 ml of ambient air, shaken for 5 minutes, and injected into a pre-evacuated 12 ml exetainer (Labco UK). The water temperature was measured in-situ and in the syringe using a HANNA Instruments (HI991300) probe. Gas concentration measurements were made using a gas chromatograph (SRI 8610C, University of Liège) with a flame ionization detector with a methanizer calibrated with $\text{CH}_4:\text{CO}_2:\text{N}_2$ gas mixtures (Air Liquide Belgium) with mixing ratios of 1, 10 and 30 ppm for CH_4 , and 404, 1018, 3961 ppm for CO_2 . The precision of measurement was $\pm 3.9 \%$ for CH_4 , and $\pm 5.0 \%$ for CO_2 .

Silicon concentration measurements

In stream waters and soil pore waters ($n = 26$), the concentration in silicon (Si) was measured by an inductively coupled plasma-optical emission spectrometer (ICP-OES, iCAP 6500 ThermoFisher Scientific). The accuracy is $\pm 0.3 \%$ and the detection limit is 0.2 mg L^{-1} .

Silicon isotope measurements

In stream waters and soil pore waters ($n = 26$), the silicon isotope composition ($\delta^{30}\text{Si}$) was measured using a MC-ICP-MS (Neptune Plus™ High Resolution Multicollector ICP-MS, Thermo Fisher Scientific, Earth and Life Institute, UCLouvain, Belgium) following the published method (Hirst *et al.*, 2023). Sample preparation was done in clean lab conditions (ISO 6) under a laminar flow hood (ISO 5). A volume equivalent to $10 \mu\text{g}$ Si was dried down. The dissolved organic carbon in solution was removed by repeated cycles of heating ($60 \text{ }^\circ\text{C}$) with concentrated HNO_3 and H_2O_2 and evaporating ($80 \text{ }^\circ\text{C}$) cycles (Hughes *et al.*, 2011). The sample was digested in 0.125 M NaOH for four hours at $100 \text{ }^\circ\text{C}$,

then acidified with HNO₃. Silicon was purified from the matrix with a one-stage column chemistry using a cation exchange resin (Biorad AG50W-X12; Georg *et al.*, 2006). The Si recovery was typically > 90% and Na⁺ concentrations below the detection limit.

The silicon isotope composition ($\delta^{30}\text{Si}$) was measured by MC-ICP-MS in wet plasma mode in high resolution ($\Delta m/m \approx 9000$) using a PFA nebulizer of 100 $\mu\text{L min}^{-1}$ uptake rate. The instrumental mass bias was corrected using the standard-sample bracketing technique and an external Mg doping (Cardinal *et al.*, 2003). The analyses were performed in 2% HNO₃ matrix, with a typical sensitivity of 3.5 V for 1 mg L⁻¹ Si and an instrumental blank < 30 mV. The $\delta^{30}\text{Si}$ compositions are expressed in relative deviations of $^{30}\text{Si}/^{28}\text{Si}$ ratio from an in-house standard (Quartz Merck) isotopically similar to NBS28 reference standard using the common δ -notation (‰) as follows (Abraham *et al.*, 2008): $\delta^{30}\text{Si} = [(^{30}\text{Si}/^{28}\text{Si})_{\text{sample}} / (^{30}\text{Si}/^{28}\text{Si})_{\text{Quartz Merck}} - 1] \times 1000$.

The long-term precision and accuracy of the MC-ICP-MS was assessed from diatomite standard measurements ($\delta^{30}\text{Si} = 1.29 \pm 0.05$ ‰, SD, n = 7) which are consistent with previously reported values ($\delta^{30}\text{Si} = 1.26 \pm 0.10$ ‰; Reynolds *et al.*, 2007).

Data treatment

All graphs and statistics were performed using R 4.0.2 (RStudio Inc., Boston, Massachusetts, USA) and plots using the ggplot2 package.

The significant differences in temperature, pH, electrical conductivity, DOC concentrations, $\Delta^{14}\text{C}$ -DOC, CO₂ and CH₄ concentrations, Si concentrations, and $\delta^{30}\text{Si}$ between locations (downstream – upstream), between core type (frozen – talik) or between years (2024 – 2025) were compared with a Wilcoxon test. The 95% confidence intervals of the statistic were used to test for a significant difference between values, which is equivalent to a p-value cutoff of 0.05 (*, p-value < 0.05; **, p-value < 0.01; ***, p-value < 0.001).

Supplementary Tables

Table S-1 Coordinates (longitude and latitude), snow depth and talik depth (top of the talik) from each core sampled in 2024 and 2025 at Eight Mile Lake (Alaska)

Core	Longitude (°)	Latitude (°)	Year	Snow depth (cm)	Talik depth (top) (cm)
O1	-149.25043498	63.87922008	2025	30	65
O2	-149.25483020	63.87771930	2025	40	50
O3	-149.24932890	63.88084321	2025	20	37
U1	-149.25755024	63.87921807	2024	30	67
U2	-149.25696778	63.87935029	2024	65	60
			2025	50	40
D1	-149.25109299	63.88166974	2024	50	60
			2025	40	37
D2	-149.25087137	63.88143836	2024	60	34
D3	-149.25027074	63.88207837	2024	50	27
			2025	20	47
D4	-149.248389574	63.8830855675	2024	80	18
			2025	10	40

Supplementary Figures

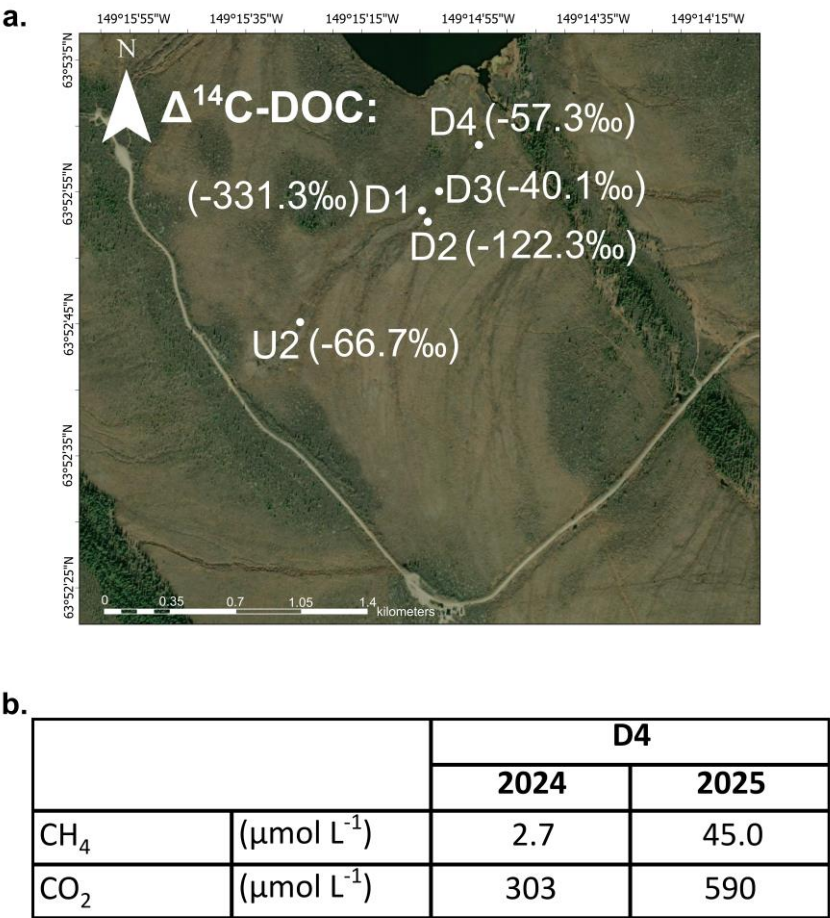


Figure S-1 (a) Radiocarbon of DOC ($\Delta^{14}\text{C-DOC}$, in ‰) in taliks from U2, D1-D4, where D4 corresponds to free-standing water collected from a shallow unconfined saturated zone at the most downstream site. **(b)** Dissolved concentration of CO₂ (in μmol L⁻¹) and CH₄ (in μmol L⁻¹) in the free-standing water from the talik at D4 in 2024 and 2025.

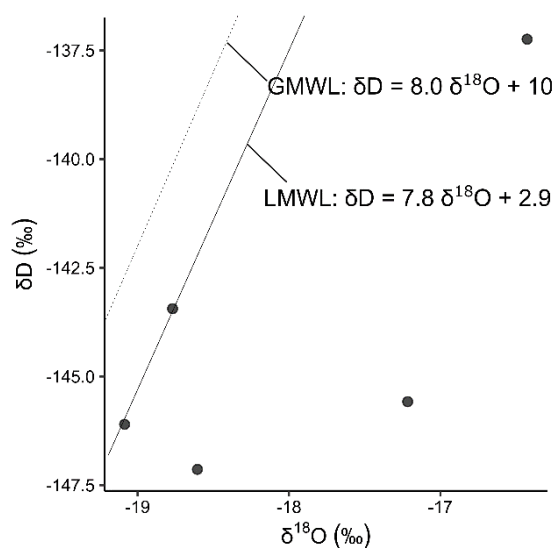


Figure S-2 ($\delta^{18}\text{O}$) and deuterium (δD) isotope composition for river waters collected in the streams (inlet and Panguingue Creek river) in 2024 and 2025. The Global Meteoric Water Line (GMWL) and the Local Meteoric Water Line (LMWL) for precipitation are presented (Hirst *et al.*, 2022).

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