

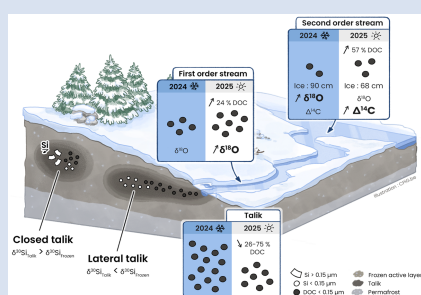
Deep winter dissolved organic carbon transfer from taliks in permafrost landscapes

M. Villani^{1*}, P. Roux¹, M. Henrion¹, S. François¹, E. du Bois d'Aische¹, L. Monin¹, A.V. Borges², A.K. Kelley³, J. Ledman³, G. Denis⁴, E.A.G. Schuur³, S. Opfergelt¹



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Abstract



In permafrost landscapes, taliks (unfrozen ground zones) represent year round hydrological pathways that can transfer dissolved organic carbon (DOC) to streams during winter. When laterally connected, taliks enhance winter hydrological flow and DOC transfer to streams, yet their connectivity and biogeochemical role remain poorly constrained. Here, we use silicon isotopes ($\delta^{30}\text{Si}$) in soil pore waters to distinguish closed from lateral taliks at a water track in Alaska, and study DOC transfer to first and second order streams across two contrasting winters (2025 warmer than 2024). Silicon isotopes emerge as a promising tracer of talik connectivity, with lateral taliks showing systematically lighter Si isotope composition than in the frozen soil, whereas closed taliks exhibit systematically heavier Si isotope compositions. Stream water data reveal enhanced transfer of younger, soil derived DOC from lateral taliks during the warmer winter, with up to 57 % higher DOC concentrations compared to the colder winter, despite similar dissolved CO_2 and CH_4 concentrations. This offers a first biogeochemical view of talik connectivity (closed/lateral) in deep winter and calls for integration with geophysical approaches to fully resolve its role in winter carbon cycling.

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Introduction

Across the northern permafrost region, 1,662 Tg of carbon *per* year is released to the atmosphere as carbon dioxide (CO_2) and methane (CH_4) during the winter season (October–April; Natali *et al.*, 2019; Arndt *et al.*, 2023). Winter carbon emissions may be preceded by subsurface mobilisation and transfer of dissolved organic carbon (DOC) within taliks (Parazoo *et al.*, 2018; Walter Anthony *et al.*, 2024; Bergman *et al.*, 2025), processes that remain poorly constrained. A talik is defined as “a part of the ground at a site with permafrost that remains unfrozen year round” (Lewkowicz *et al.*, 2024) and may be either between the base of the active layer and permafrost (supra-permafrost talik), or within a permafrost profile (intra-permafrost talik; Devoie *et al.*, 2024). Supra-permafrost taliks can be either closed or lateral (O'Neill *et al.*, 2020): closed taliks are surrounded by frozen ground with talik water relatively stagnant, having only a localised sphere of influence and limited flow potential; and lateral taliks can form lateral water flow pathways, leading to an increase in DOC transfer from soil to streams in winter (Connon *et al.*, 2018; Devoie *et al.*, 2024). Thus, distinguishing between closed and lateral taliks is crucial for determining how supra-permafrost taliks regulate winter carbon transfer from soils to streams (Kurylyk and Walvoord, 2021; Zhao *et al.*, 2026).

Water tracks are unchanneled zones overlying permafrost that concentrate water flow downslope, and exhibit higher soil moisture and snow thickness than the surrounding areas (Del Vecchio and Evans, 2025). Moreover, soil moisture increases along the water tracks, leading to wetter areas downstream of the water tracks, mainly fed by water from upstream during the growing season (Tananaev *et al.*, 2021). Increasing soil moisture associated with water flows enhances advective heat transfer, promoting the development of taliks, potentially favouring closed taliks where the soil moisture is lower upstream, and lateral taliks where the soil moisture is higher downstream of the water track (Devoie *et al.*, 2021). Existing methods for talik detection are based on mechanical, geophysical and thermal approaches (O'Neill *et al.*, 2020). The gap in biogeochemical methods reflects the exceptional logistical challenges of collecting soil pore water from taliks during deep winter, when frozen surface conditions and extreme cold make *in situ* sampling difficult.

Talik connectivity may be assessed using the stable isotope composition of silicon ($\delta^{30}\text{Si}$), based on Hirst *et al.* (2023), who measured $\delta^{30}\text{Si}$ in soil pore waters to distinguish isolated from connected soil pore water during the late winter to snow melt transition. We apply it here to a colder, earlier stage of winter, prior to any onset of thaw. Upon freezing of soil pore water under a closed system, the decrease in liquid water volume drives an increase in the silicic acid concentration in soil pore waters

1. Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium
2. Chemical Oceanography Unit, University of Liège, Liège, Belgium
3. Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, AZ, USA
4. Imaqa Expeditions, Brussels, Belgium
* Corresponding author (e-mail: maelle.villani@uclouvain.be)

over the amorphous silica solubility (Dietzel, 2005). Amorphous silica precipitation induces silicon isotope fractionation by preferentially incorporating lighter isotopes into solid phases (from nanosized solid phases termed colloids to particulate sized phases), leaving the dissolved soil pore water fraction isotopically heavier (Oelze *et al.*, 2015). This process may happen in closed taliks (Hirst *et al.*, 2023), leaving the soil pore water from taliks isotopically heavier than soil pore water from the surrounding frozen soil (soil pore water $\delta^{30}\text{Si}_{\text{talik}} > \delta^{30}\text{Si}_{\text{frozen}}$). In lateral taliks, water flow prevents silicic acid concentration. In addition, the freezing front facilitates colloid mobilisation through preferential flow paths (Mohanty *et al.*, 2014) from the frozen ground to the lateral talik. This leads to a soil pore water isotopically lighter in lateral taliks with the accumulation of light $\delta^{30}\text{Si}$ bearing-colloids compared to the surrounding frozen soil (soil pore water $\delta^{30}\text{Si}_{\text{talik}} < \delta^{30}\text{Si}_{\text{frozen}}$).

This study aims to biogeochemically distinguish supra-permafrost taliks located upstream, downstream, and outside a water track from Eight Mile Lake (Healy, Alaska; Fig. 1), using soil pore water chemistry (pH, conductivity, DOC concentrations, and $\delta^{30}\text{Si}$) from the taliks and the frozen portions of the soil within the active layer. The chemistry of local first order (inlet) and second order stream waters (Panguingue Creek River) is investigated to assess the implications of talik connectivity for DOC transfer to streams (pH, conductivity, $\delta^{18}\text{O}$, DOC concentrations, radiocarbon of DOC ($\Delta^{14}\text{C}$ -DOC), dissolved CO_2 and CH_4 concentrations, Si concentrations, and $\delta^{30}\text{Si}$). As winters become increasingly warmer in permafrost regions (Graham *et al.*, 2017), we compare two contrasted winters to examine how interannual differences in air temperature (winter 2025 warmer than winter 2024) influence carbon transfer to streams (see SI).

Contrasting Interannual Winter Conditions

At Eight Mile Lake, winter air temperatures in 2023–2024 and 2024–2025 were significantly higher compared to the previous ten winters ($-11.3 \pm 9.1^\circ\text{C}$; $p < 0.001$; Wilcoxon test; Kennedy *et al.*, 2026), and the winter freezing degree day was higher in 2024–2025 (-1528°C) than in 2023–2024 (-1911°C ; calculated by summing all negative values between 1 November and 14 May; Farquharson *et al.*, 2022). Winter 2024–2025 was then warmer than winter 2023–2024 overall, and this was also observed more specifically during the sampling period (February–March): air temperatures were significantly higher (p value < 0.001) of 1.9°C in 2025 ($-7.4 \pm 6.9^\circ\text{C}$ (mean $\pm$ s.d.) with a minimum of -25°C) than in 2024 ($-9.3 \pm 10.6^\circ\text{C}$ (mean $\pm$ s.d.) with a minimum of -34°C ; Fig. 1d). As a result, February–March soil temperatures were significantly higher (p value < 0.001) in 2025 than in 2024 for each depth at each site, with increases ranging from 1.5 to 2.4°C (Fig. 1e). Snow depth at the site was thinner both upstream and outside of the water track in 2025 (15 ± 8 cm, $n = 6$) than in 2024 (23 ± 13 cm, $n = 6$; Fig. 1b). Despite a large variability in snow depth, this trend is consistent with regional observations of thinner snow depth in 2025 (42 ± 23 cm) than in 2024 (50 ± 23 cm) in Healy (Thompson *et al.*, 2025). These contrasting air and soil temperatures and snow layer thicknesses between the two winters may then influence talik biogeochemical connectivity.

Chemical Composition of the Soil Pore Waters and Streams

In soil pore waters from the taliks and the frozen portions of the soil, pH, conductivity, and DOC concentrations varied from 2.9 to 5.1 (3.9 ± 0.6), 10.3 to 105 $\mu\text{S cm}^{-1}$ ($53.5 \pm 28.5 \mu\text{S cm}^{-1}$), and

25.4 to 299 mg L^{-1} ($100 \pm 59.0 \text{ mg L}^{-1}$) respectively (Fig. 2a–c). In soil pore waters from the taliks sampled both in 2024 and 2025 ($n = 6$; upstream and downstream of the water track), DOC concentrations are 45 (U2), 26 (D1) and 75 % (D3) lower in 2025 compared to 2024, respectively, suggesting DOC dilution within a wetter water track under warmer conditions in 2025 (Del Vecchio and Evans, 2025).

At the inlet (first order stream), water pH and conductivity varied respectively between 6.3 and 4.3, and between 136 and 65 $\mu\text{S cm}^{-1}$ (Fig. 2, Table 1). Water $\delta^{18}\text{O}$ values and DOC concentrations were respectively 4 % and 24 % higher in 2025 compared to 2024. Values of $\Delta^{14}\text{C}$ -DOC were slightly higher in 2025 (-1.7‰) than in 2024 (-19.4‰), corresponding to young DOC radiocarbon ages of ~ 0 and 86 years BP, respectively, potentially derived from recently fixed plant litter in the downslope area close to the inlet (Benner *et al.*, 2004). Dissolved CO_2 and CH_4 concentrations in inlet waters were considered stable between 2024 ($420 \mu\text{mol L}^{-1} \text{CO}_2$ and $19.4 \mu\text{mol L}^{-1} \text{CH}_4$) and 2025 ($443 \mu\text{mol L}^{-1} \text{CO}_2$ and $11.9 \mu\text{mol L}^{-1} \text{CH}_4$) given the typical variability of these quantities in streams in permafrost areas (Street *et al.*, 2016).

At the Panguingue Creek River (second order stream), water pH and conductivity varied respectively between 7.4 and 6.0, and between 274 and 317 $\mu\text{S cm}^{-1}$ (Fig. 2, Table 1). Water $\delta^{18}\text{O}$ values were 3 % lower, and DOC concentrations were 57 % higher in 2025 compared to 2024. Values of $\Delta^{14}\text{C}$ -DOC were higher (*i.e.* less depleted) in 2025 (-508.2‰ , 5628 years BP) compared to 2024 (-521‰ , 5841 years BP), indicating a younger DOC source in 2025. Dissolved CO_2 and CH_4 concentrations remained similar in 2024 ($139 \mu\text{mol L}^{-1} \text{CO}_2$ and $0.030 \mu\text{mol L}^{-1} \text{CH}_4$) and 2025 ($91 \mu\text{mol L}^{-1} \text{CO}_2$ and $0.045 \mu\text{mol L}^{-1} \text{CH}_4$) in the Panguingue Creek River water, in agreement with the absence of changes observed at the inlet.

Silicon Isotopes Reveal Talik Connectivity (Closed versus Lateral)

In soil pore waters from the taliks and from the frozen portions of the soil, Si concentrations varied from 4.0 to 18.1 mg L^{-1} , and the silicon isotope compositions ($\delta^{30}\text{Si}$) varied from -0.02 to 2.88 ‰ (Fig. 2d–e). To characterise talik connectivity (closed *versus* lateral), we consider the difference in $\delta^{30}\text{Si}$ values between soil pore waters from the taliks and from the frozen portions of the soil, *i.e.* the $\Delta_{\text{Frozen-Talik}}\delta^{30}\text{Si}$ (Fig. 2f).

In 2024, the $\Delta_{\text{Frozen-Talik}}\delta^{30}\text{Si}$ (Fig. 2f) had two distinct patterns depending on the locations of the cores along the slope: upstream of the water track, $\delta^{30}\text{Si}$ was higher in the taliks than in the frozen portions of the soil ($\Delta_{\text{Frozen-Talik}}\delta^{30}\text{Si} < 0$) with a mean difference of -1.08‰ ; whereas downstream of the water track, $\delta^{30}\text{Si}$ was lower in the taliks than in the frozen portions of the soil ($\Delta_{\text{Frozen-Talik}}\delta^{30}\text{Si} > 0$) with a mean difference of $+0.86\text{‰}$, consistent with Si isotope fractionation during freezing processes (Hirst *et al.*, 2023). Upstream of the water track ($\delta^{30}\text{Si}_{\text{talik}} > \delta^{30}\text{Si}_{\text{frozen}}$), the heavier signature is consistent with closed system Si isotopic fractionation (Hatton *et al.*, 2019): in *closed taliks*. Downstream of the water track ($\delta^{30}\text{Si}_{\text{talik}} < \delta^{30}\text{Si}_{\text{frozen}}$), the lighter signature indicates an open system without Si isotopic fractionation in *lateral taliks*. Downstream taliks were also shallower (40 ± 17 cm) than upstream (64 ± 5 cm; Fig. 1b, Table S-1), consistent with a wetter, more connected zone that may transfer carbon to streams in deep winter.

In 2025, $\Delta_{\text{Frozen-Talik}}\delta^{30}\text{Si}$ was negative upstream of the water track and positive downstream of the water track, which confirms the results obtained in 2024 (Fig. 2f): closed taliks are upstream and lateral taliks are downstream of the water track.

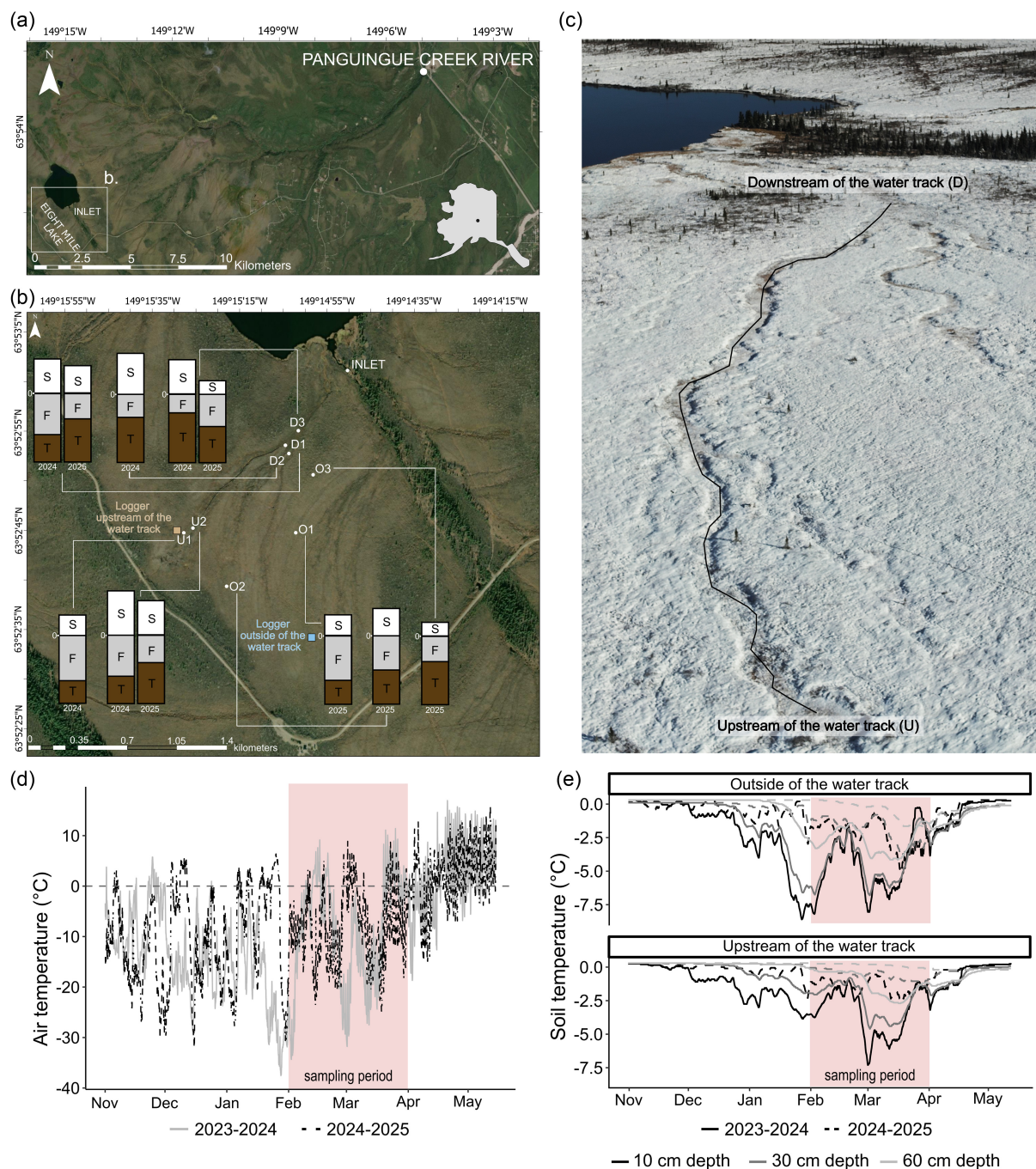


Figure 1 (a) Eight Mile Lake (details in (b)), the first order stream (inlet), and the second order stream (Panguingue Creek River). (b) Study site showing core positions outside (O1-O3), upstream (U1-U2), and downstream (D1-D3) of the water track, the inlet, and temperature loggers; core schematics show snow depth (S), frozen soil thickness (F), and talik depth (T), to scale (Table S-1). (c) Drone photograph (October 2023) showing the water track. (d) Air and (e) soil temperatures (10, 30, 60 cm depth) from November 1 to May 15 at locations in (b).

Moreover, $\delta^{30}\text{Si}$ values from soil pore waters outside of the water track exhibit patterns similar to those measured upstream of the water track: $\Delta_{\text{Frozen-Talik}} \delta^{30}\text{Si}$ was negative with $\delta^{30}\text{Si}$ in the taliks and 0.70 ‰ higher than in the frozen portions of the soil. As a result, taliks from outside of the water track are closed, like upstream of the water track.

Tracing Lateral Talik Contributions to Streams Using Silicon Isotopes

At the inlet (first order stream), dissolved Si concentrations and $\delta^{30}\text{Si}$ values were 47 % and 35 % lower, respectively, in

2025 compared to 2024 (Fig. 2d,e, Table 1). Inlet $\delta^{30}\text{Si}$ was lower in 2025 (1.33 ‰) than in 2024 (2.04 ‰), a shift toward lighter values, consistent with an increased contribution of soil pore waters from lateral taliks (0.59 ± 0.58 ‰) in 2025. The increase in $\delta^{18}\text{O}$ values from the inlet waters in 2025 compared to 2024 also supports this higher contribution of soil pore waters under warmer conditions (Table 1; Hirst *et al.*, 2022). As a result, our data suggest that, under warmer conditions (2025), winter inlet waters reflect an increased input from lateral talik pore waters, in addition to a persistent contribution from deep sub-permafrost groundwater (O'Donnell *et al.*, 2012; Roux *et al.*, 2026).

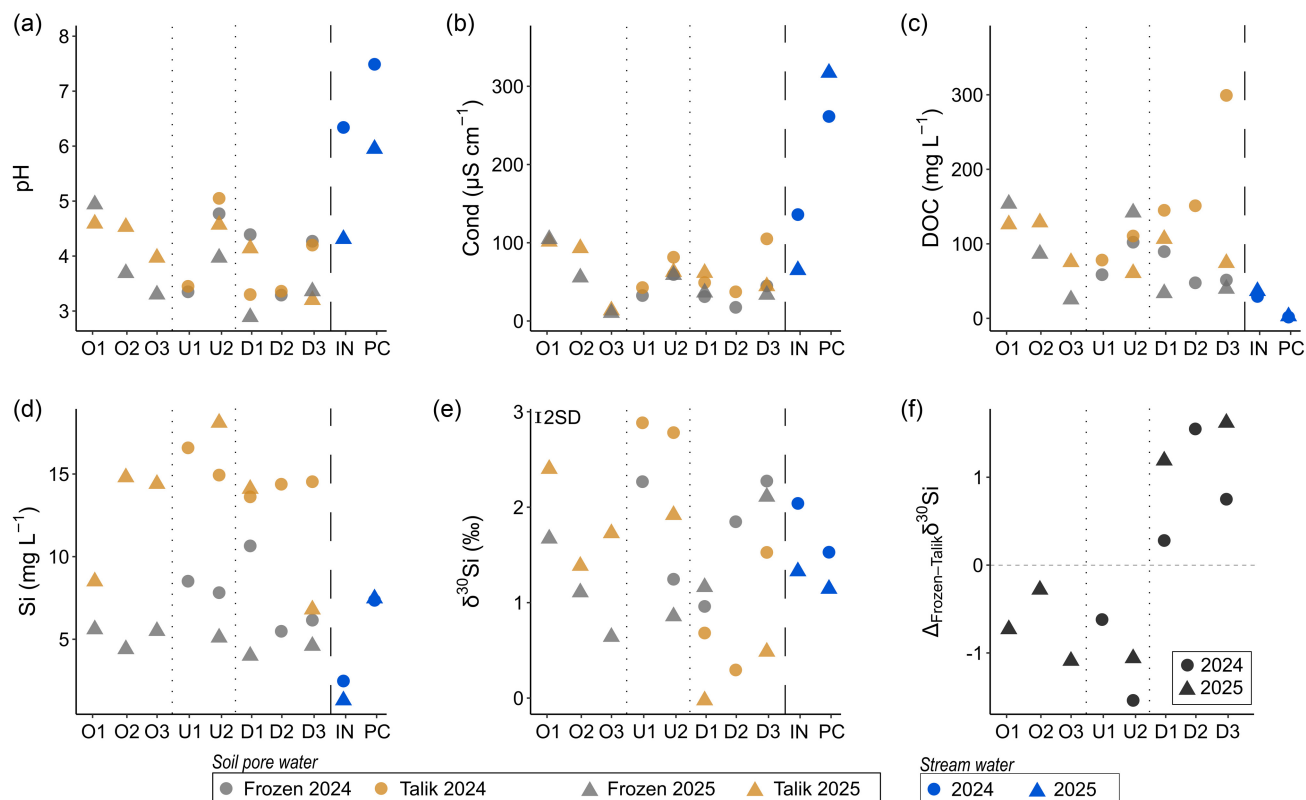


Figure 2 (a) pH, (b) conductivity ($\mu\text{S cm}^{-1}$), (c) DOC and (d) Si concentration (mg L^{-1}), (e) $\delta^{30}\text{Si}$ (‰), and (f) $\Delta_{\text{Frozen-Talik}} \delta^{30}\text{Si}$ in soil pore waters from the taliks (in yellow; $n = 11$) and the frozen portions of the soil (in grey; $n = 11$) from coring outside (O), upstream (U), and downstream (D) of the water track in 2024 and 2025; and in stream waters ($n = 4$; in blue: IN = inlet and PC = Panguingue Creek River; Table 1).

Table 1 pH, conductivity ($\mu\text{S cm}^{-1}$), water isotopes ($\delta^{18}\text{O}$ and δD , ‰), DOC concentration (mg L^{-1}), $\Delta^{14}\text{C}$ -DOC (‰), dissolved concentrations of CO_2 ($\mu\text{mol L}^{-1}$) and CH_4 ($\mu\text{mol L}^{-1}$), Si concentrations (mg L^{-1}), and $\delta^{30}\text{Si}$ (‰) from the inlet and the Panguingue Creek River. (*) Shown in Figure 2.

Parameters (units)	Inlet (first order stream)		Panguingue Creek River (second order stream)	
	2024	2025	2024	2025
*pH (-)	6.3	4.3	7.4	6.0
*Conductivity ($\mu\text{S cm}^{-1}$)	136	65	274	317
$\delta^{18}\text{O}$ (‰)	-17.2	-16.4	-18.5	-19.1
δD (‰)	-145.6	-137.2	-148.2	-146.1
*DOC (mg L^{-1})	29.4	36.6	1.7	2.7
$\Delta^{14}\text{C}$ (‰)	-19.4	-1.7	-521.0	-508.2
CO_2 ($\mu\text{mol L}^{-1}$)	420	443	139	91
CH_4 ($\mu\text{mol L}^{-1}$)	19.4	11.9	0.030	0.045
*Si (mg L^{-1})	2.5	1.3	7.5	7.5
* $\delta^{30}\text{Si}$ (‰)	2.04	1.33	1.71	1.14

At the Panguingue Creek River (second order stream), Si concentrations remained similar in 2024 and 2025 (7.5 mg L^{-1}), and $\delta^{30}\text{Si}$ values were 33 % lower in 2025 compared to 2024 (Fig. 2d,e, Table 1). Panguingue Creek $\delta^{30}\text{Si}$ was lower in 2025 (1.14 ‰) than in 2024 (1.71 ‰), a shift toward lighter values, consistent with an increased contribution of soil pore waters from lateral taliks (0.59 ± 0.58 ‰) in 2025, similar to the pattern observed at the inlet. The decrease in $\delta^{18}\text{O}$ in 2025 compared to 2024 (Table 1) likely reflects intra-river processes (Gibson and Prowse, 2002), including reduced river ice thickness during the warmer winter (90 cm in 2024 and 68 cm in 2025; see SI), rather than a direct soil signal. This indicates that Panguingue

Creek, as a second order stream, reflects an increased input from talik pore waters under warmer conditions (2025), in addition to a persistent contribution from deep sub-permafrost ground-water (O'Donnell *et al.*, 2012; Roux *et al.*, 2026), and intra-river processes.

Implications for Winter Carbon Mobilisation and Transfer into Streams

Lateral taliks being hydrologically connected during winter (Zhao *et al.*, 2026), they likely enhance the transfer of DOC to

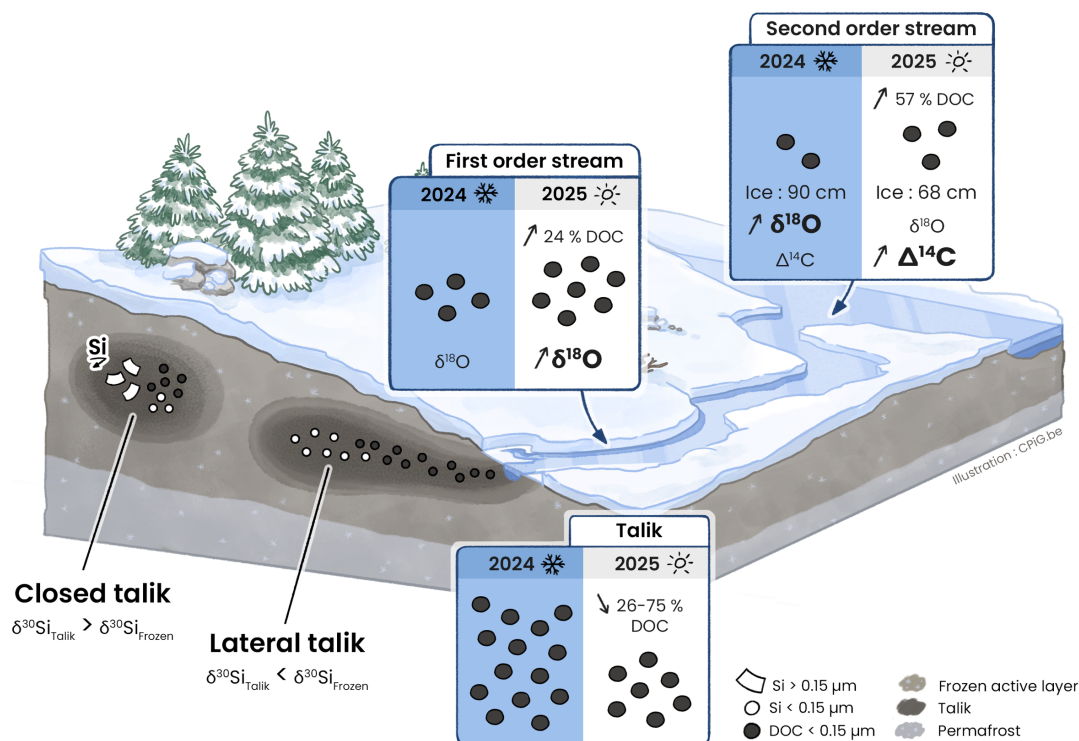


Figure 3 Synthesis of winter biogeochemical processes in between February-March 2024 and 2025. The first order stream represents the inlet, and the second order stream represents the Panguingue Creek River in this study. (The figure was designed by CPIG-Carolina Levicek)

streams. As the sampling period in 2025 was warmer than in 2024, the increase in DOC concentrations in the first and the second order stream waters in 2025 compared to 2024 suggests an increase in this mobilisation and the transfer of DOC from soils to streams (Fig. 3). The parallel increase in $\Delta^{14}\text{C}$ values at the second order stream (from -521.0 in 2024 to -508.2 ‰ in 2025; Table 1) under warming conditions also supports a greater contribution of younger DOC from talik pore waters ($\Delta^{14}\text{C}$ -DOC = -123.5 ± 120.2 ‰; Fig. S-1a). This increase in transfer of young DOC from lateral taliks in 2025 is in line with $\delta^{30}\text{Si}$ and $\delta^{18}\text{O}$ values at the first order stream, and $\delta^{30}\text{Si}$ at the second order stream (Fig. 2, Table 1). Stream waters were sampled once *per* year at each site, precluding formal statistical testing of interannual differences. However, the consistent direction of change across several independent parameters (DOC concentration, $\Delta^{14}\text{C}$ -DOC, $\delta^{30}\text{Si}$, and $\delta^{18}\text{O}$) demonstrates that these shifts reflect an increase in lateral talik contribution to streams under warmer conditions, rather than sampling variability alone.

At both the first and second order streams, dissolved CO_2 and CH_4 concentrations were stable between 2024 and 2025, (Table 1), suggesting that the mobilisation of DOC from lateral taliks in 2025 compared to 2024 does not translate into a change in the production of CO_2 and CH_4 and transfer to streams. A similar decoupling between DOC mobilisation and CO_2/CH_4 production was reported in Yedoma thaw affected lakes, where highly labile permafrost DOC nonetheless accumulated rather than being rapidly mineralised (Ollivier *et al.*, 2026). This decoupling contrasts with conditions in the soil itself: in free standing water from a shallow unconfined saturated zone at the most downstream site (Fig. S-1b; D4), dissolved CO_2 and CH_4 concentrations increased ~ 2 and ~ 17 fold, respectively, between 2024 ($\text{CO}_2 = 303 \mu\text{mol L}^{-1}$, $\text{CH}_4 = 2.7 \mu\text{mol L}^{-1}$) and 2025 ($\text{CO}_2 = 590 \mu\text{mol L}^{-1}$, $\text{CH}_4 = 45.0 \mu\text{mol L}^{-1}$), pointing to stronger CO_2 and CH_4 production in saturated soils under warmer conditions. This enhanced soil production, however, provides no

evidence of a corresponding transfer of dissolved CO_2 and CH_4 to streams. Alternatively, we cannot exclude that part of the transferred DOC is mineralised along the flow path between the first and second order streams, without being captured by our fixed point sampling. Enhanced winter DOC transfer from lateral taliks and active microbial CO_2 and CH_4 production in talik soils (Fig. S-1b) may also have delayed effects on riverine greenhouse gas dynamics during subsequent high flow period after deep winter (Castro-Morales *et al.*, 2022), contributing to the permafrost driven increase in annual stream CO_2 emissions (Mu *et al.*, 2025).

Conclusion

This study provides geochemical evidence of lateral talik connectivity using silicon isotopes. Contrasting $\delta^{30}\text{Si}$ signatures between taliks and frozen soil pore waters (heavier upstream and lighter downstream of the water track) distinguish closed from lateral taliks. The higher DOC concentrations in stream waters in 2025 than in 2024 suggest a greater lateral talik contribution to streams under warmer conditions. Together, these results indicate that lateral taliks act as critical subsurface pathways linking winter soil pore waters DOC mobilisation to aquatic carbon cycling. As winters continue to warm, the expansion of lateral taliks may enhance DOC transfer to streams, but do not necessarily lead to immediate increases in riverine dissolved CO_2 and CH_4 concentrations during winter. This study represents a first step toward understanding talik biogeochemical connectivity, given the logistical challenges of winter sampling in remote permafrost environments. Expanding observations across multiple sites and combining geochemical tracers with existing geophysical and thermal characterisation of taliks will be essential to fully assess the biogeochemical significance of lateral taliks in permafrost ecosystems.

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Data Availability

The data related to this article is available online at: <https://doi.org/10.14428/DVN/LPFBWO>

Additional Information

Supplementary Information accompanies this letter at <https://www.geochemicalperspectivesletters.org/article2636>.

During the preparation of this work the author used ChatGPT in order to assist with language editing and rephrasing of specific sentences. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.



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