



Ideas and perspectives: the biogeochemical role of taliks

Maëlle Villani¹, Louise M. Farquharson², Vladimir E. Romanovsky², Sophie Opfergelt¹

¹Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium

² Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, United States of America

5 Correspondence to : Maëlle Villani (maelle.villani@uclouvain.be)

Abstract

Taliks, unfrozen ground within permafrost, sustain year-round biogeochemical processes, mobilizing carbon, nutrients, and contaminants through lateral and open taliks, while closed and isolated taliks confine reactions locally. Yet, while talik physical and thermal dynamics have been increasingly documented, their biogeochemical processes remain understudied, particularly in winter. In this manuscript, we argue that taliks represent a critical and overlooked driver of Arctic and sub-Arctic biogeochemical processes. We put forward three testable hypotheses to advance the study of talik biogeochemical functioning and we propose a related road map: year-round sampling, standardized protocols, pan-Arctic talik mapping, and community-building.

1. Introduction

Permafrost, ground that remains frozen for at least two consecutive years, underlies a seasonally frozen surface layer (Schoolmeester et al., 2023). Taliks are defined as 'a part of the ground at a site with permafrost that remains unfrozen throughout the year' (Lewkowicz et al., 2024). Taliks may have a temperature above 0°C (non-cryotic) or below 0°C (cryotic; e.g., in saline environments; Millero et al., 2008). Taliks can be described based on a number of characteristics (Fig. 1; Lewkowicz et al., 2025) : (1) relationship to permafrost (e.g., supra-permafrost, intra-permafrost, and through); (2) hydrological connectivity or geometry (e.g., lateral, open, closed, and isolated); (3) processes leading to their formation (e.g., hydrothermal taliks are maintained above 0°C by heat from flowing groundwater, and hydrochemical taliks are maintained below 0°C by mineralized groundwater flow that limits freezing; O'Neill et al., 2020); (4) associated landscape features (e.g., sub-aerial, sub-aqueous, and sub-glacial); and (5) temporal dynamics (e.g., transient talik that temporally refreezes). Talik formation has accelerated in recent decades as permafrost thaws from above and below, with sub-aerial taliks increasingly reported across Arctic and sub-Arctic landscapes, alongside the more widely recognized sub-aqueous taliks (Connon et al., 2018; Farquharson et al., 2022; O'Neill et al., 2020; Parazoo et al., 2018; Wang & Niu, 2024). Sub-aerial taliks are estimated to grow vertically at ~0.13–0.25 m yr⁻¹, comparable to the 0.1–0.5 m yr⁻¹ rates reported for sub-lake taliks over centuries (Wellman et al., 2013), though these estimates remain limited to vertical thaw, with volumetric extent still unconstrained (Luo et al., 2025).

There is emerging evidence that different talik types create distinct hydrological (water transfer), thermal (heat transfer) and biogeochemical (dissolved ions and gas transfer) connectivity pathways, but this interplay remains poorly constrained. To date, talik research has focused almost exclusively on their physical detection, formation, and thermal evolution (Farquharson et al., 2022; O'Neill et al., 2020; Wang & Niu, 2024); their role in sustaining biogeochemical processes, such as carbon, nutrient, and contaminant cycling year-round, has not yet been investigated. In this manuscript, we raise the question of whether the year-round presence of liquid water within



taliks creates hotspots of disproportionately high reaction rates for biogeochemical processes particularly in winter. We also explore the consequences of increasing talik prevalence on biogeochemical processes and connectivity, and more specifically the mobilization of carbon, nutrients and contaminants under a warming climate. Finally, we argue that talik expansion, already committed and irreversible on human timescales, demands a timely and coordinated interdisciplinary effort (spanning geophysics, hydrology, biogeochemistry, microbiology, and industry) essential to characterize these processes and anticipate their consequences for Arctic and global biogeochemical cycling.

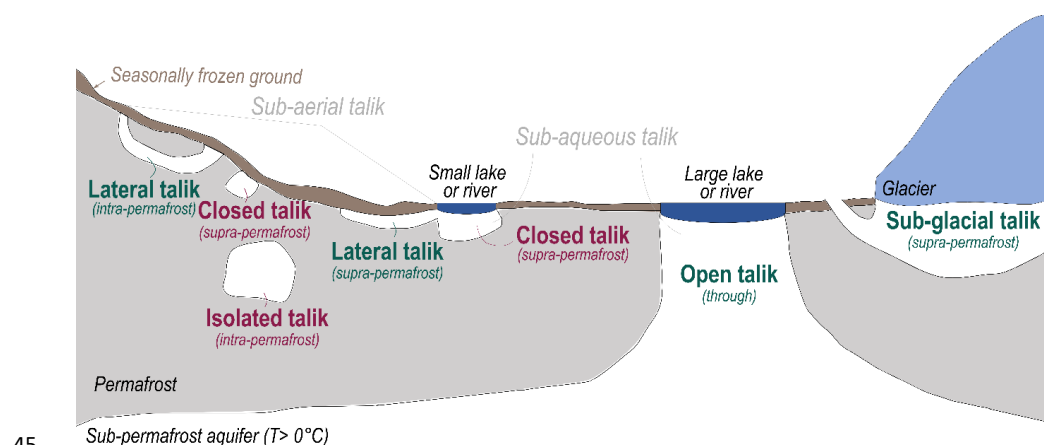


Figure 1 : Talik configurations (supra-permafrost, intra-permafrost, through) and hydrological connectivity (lateral, open, closed, and isolated; adapted from O'Neill et al., 2020). Based on their position relative to permafrost, taliks are classified as supra-permafrost (above the permafrost layer), intra-permafrost (within the permafrost layer), or through taliks (extending through the entire permafrost layer). Based on their hydrological connectivity, they range from isolated and closed taliks, surrounded by frozen ground where biogeochemical reactions are confined (in red), to lateral and open taliks, where water transfer enables solute export across the landscape (in green). Sub-aqueous taliks form beneath aquatic bodies, while sub-aerial taliks form directly within upland soils. The sub-permafrost aquifer ($T > 0^{\circ}\text{C}$) at depth can connect to surface waters where open taliks are present.

2. Biogeochemical functioning of taliks

2.1. Talik types determine hydrological and biogeochemical connectivity

The prevalence of sub-aerial taliks has been observed to increase dramatically: supra-permafrost taliks rose from 20% to 48% (*i.e.*, proportion of monitored points, based on supra-permafrost layer thickness measurements) between 2011 and 2015 in lowland tundra landscapes of sub-Arctic Canada (Connon et al., 2018), while sub-aerial talik presence increased by 43% (*i.e.*, proportion of monitored points, based on soil temperature measurements) between 2012 and 2019 in the discontinuous permafrost zone of Alaska (Farquharson et al., 2022). The overall extent of taliks relative to non-talik areas remains poorly constrained, but the areal extent of sub-aerial taliks is



predicted to increase during the current century (Nicolsky et al., 2017). This increase in talik distribution creates
 65 potential for widespread biogeochemical activity year-round. However, the magnitude and nature of these
 biogeochemical responses depend strongly on talik type, as different formation pathways give rise to distinct
 reaction environments (Parazoo et al., 2018; Walvoord et al., 2019). On one hand, closed and isolated taliks (Fig.
 1) store liquid water (and energy) within a depression surrounded by frozen ground on all sides (Devoie et al.,
 2024; Lamontagne-Hallé et al., 2018). As a result, biogeochemical reactions are confined in these talik types. On
 70 the other hand, in laterally connected taliks such as lateral and open taliks (Fig. 1), water transfer increases
 hydrological connectivity both vertically and laterally as taliks expand (Lamontagne-Hallé et al., 2018). Vertical
 connectivity occurs when supra- and sub-permafrost aquifers connect, such as when a talik forms below lakes or
 rivers (e.g., open talik; Heslop et al., 2015; Meisel et al., 2021; Rangel et al., 2021), whereas lateral connectivity
 arises from subsurface water flow through unfrozen ground that links adjacent thawed zones across the landscape
 75 and ultimately connects to aquatic bodies, a pathway associated with lateral and open taliks (Kurylyk & Walvoord,
 2021; Walvoord et al., 2012). This connectivity can also operate in the reverse direction: as permafrost thaw
 promotes talik formation below streams, previously gaining stream sections can shift to losing stream sections,
 where stream water and dissolved material infiltrate into the underlying talik and surrounding soils (Liljedahl et
 al., 2020). Consequently, the products of biogeochemical reactions in these talik types can affect wider areas
 80 depending on the magnitude and timing of the hydrological connectivity, which allows solutes (dissolved ions and
 gases) to be transferred and creates biogeochemical connectivity. As permafrost thaw progresses, this connectivity
 is expected to evolve from isolated patches toward increasingly continuous networks, and ultimately, landscapes
 underlain by extensive supra-permafrost taliks (Devoie et al., 2019). Direct field evidence remains scarce, though
 an emerging example comes from an Interior Alaska headwater stream, where winter baseflow radiocarbon and
 85 strontium isotope signatures have been interpreted as evidence of a winter talik source (Roux et al., 2026).
 Determining talik type and distribution is therefore essential for assessing subsurface hydrological connectivity
 and the potential for groundwater–surface water exchange.

2.2. Taliks enhance biogeochemical reactions

Within taliks, the presence of liquid water generates the conditions for biogeochemical reactions (Fig. 2). Taliks
 90 surrounded by frozen ground on all sides (mainly closed and isolated taliks) increase water-ground contact time
 relative to open or laterally connected taliks, thereby promoting biogeochemical reactions (Ma et al., 2019). In
 addition, shifts in redox conditions may occur in taliks, driven by seasonal changes in soil saturation, oxygen
 availability, and water flow associated with freeze–thaw dynamics, resulting in different dynamic environments
 over seasons, including winter (Herndon et al., 2020). These physico-chemical conditions within taliks can modify
 95 the mobility of elements, including redox-sensitive metals, dissolved organic carbon (DOC), and contaminants
 such as trace metal elements and black carbon.

Within taliks, liquid water activates microorganisms and also unlocks considerable amounts of carbon and
 nutrients that can be used for their accelerated growth (Jansson & Taş, 2014). Beyond the presence of liquid water
 itself, temperature within taliks can also rise above 0°C, further stimulating microbial activity (Heslop et al., 2019;
 100 Voggenreiter et al., 2025). As a result, microbial decomposition of DOC ($\Delta^{14}\text{C}$ -DOC from -180 to -573‰; Kelley
 et al., 2026) and soil organic carbon (SOC) releases CO₂ and CH₄ and contributes to total permafrost carbon
 emissions (Schoor et al., 2022; Strauss et al., 2025; Walter Anthony et al., 2024), including CH₄ from upland



Yedoma taliks (Heslop et al., 2019; Walter Anthony et al., 2024). However, a portion of this OC (organic carbon) can be bound to minerals, by adsorption onto iron oxides or complexation with metals such as iron (Hirst et al., 2022; Opfergelt, 2020), and this can modulate the availability of OC for microbial decomposition (Patzner et al., 2022). These talik carbon emissions, which persist through winter, occur alongside a broader pattern of winter carbon emissions, modeled at around 1,662 TgC per year independent of talik presence (Grogan & Chapin, 1999; Natali et al., 2019). As talik formation is a small-scale process, it remains poorly captured by process-based models and is more reliably detected through *in situ* measurements (Natali et al., 2019). Widespread talik formation is projected across 14 million km² of the permafrost region by 2300, of which 6.2 million km² is projected to become a long-term C source, emitting 10 PgC by 2100, 50 PgC by 2200, and 120 PgC by 2300 as greenhouse gases, with few signs of slowing down (Parazoo et al., 2018). As OC decomposition occurs in taliks all year, there is a need to quantify carbon that could be emitted as greenhouse gases across all seasons.

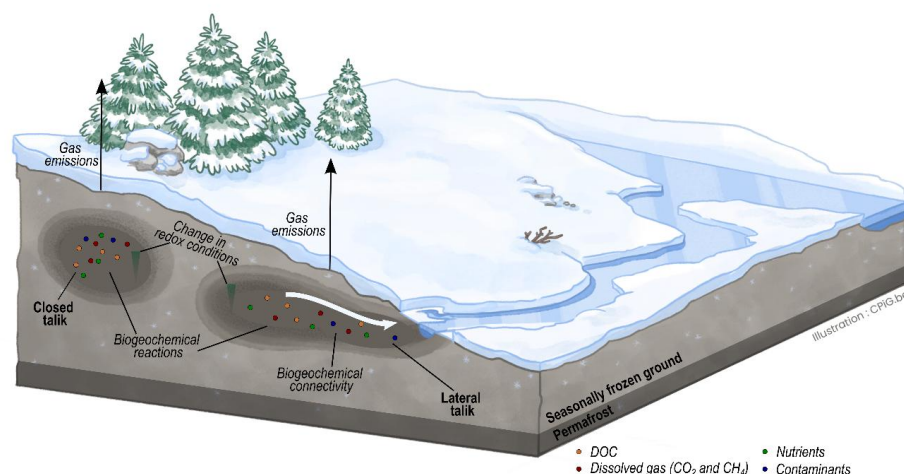


Figure 2 : Contrasting biogeochemical roles of closed and lateral supra-permafrost taliks during winter (illustration adapted from CPIG.be). In closed taliks, the absence of hydrological connectivity confines biogeochemical reactions within the talik. In lateral taliks, hydrological connectivity enables biogeochemical connectivity, with the lateral transfer of dissolved organic carbon (DOC), nutrients, and contaminants toward aquatic systems.

3. Lateral and open taliks enhance biogeochemical connectivity

In lateral and open taliks, hydrological connectivity with water transfer and permeability induces biogeochemical connectivity with the transfer of nutrients and other solutes (Liu et al., 2021). The extent of this connectivity is, however, strongly controlled by the hydraulic conductivity of the ground material, which remains low in fine-grained sediments such as silt and especially clay, even in their unfrozen state (Ebel et al., 2019). Where



permeability is sufficient, these taliks sustain subsurface flow and promote biogeochemical exports across permafrost landscapes (Fig. 2; Quinton et al., 2019; Walvoord et al., 2019).

3.1. Lateral and open taliks increase carbon mobilization, mineralization, and nutrient release

130 Organic-rich material concentrated in the active layer can be mobilized by subsurface water flow (Walvoord et al., 2019), and subsequently transferred to streams (Plaza et al., 2019; Walvoord & Striegl, 2007), with lateral and open taliks enabling this delivery of DOC year-round. Talik formation can then lead to the export to rivers (Kelley et al., 2026) of aged DOC and weathering products previously preserved in frozen organic-rich soil horizons (Roux et al., 2026; Schwab et al., 2020). Increased release of mineral elements can destabilize mineral-bound DOC by
 135 promoting non-photo and photo-mediated oxidation of permafrost-derived DOC (Bowen et al., 2020), increasing DOC bioavailability and susceptibility to further degradation. This destabilization, combined with the broader biogeochemical connectivity induced by lateral taliks, drives DOC mineralization (Lawrence & Slater, 2008). In addition to carbon, large nitrogen (N) stocks are stored in permafrost soils (estimated at 22-106 Gt N) and may be affected by talik formation through the mobilization of dissolved nitrogen into aquatic systems, with potential N₂O
 140 emissions (Bergman et al., 2025; Strauss et al., 2025). However, despite the magnitude of these solid-phase nitrogen reservoirs, the role of taliks in regulating nitrogen release and transformation in dissolved form remains largely unconstrained.

3.2. Lateral and open taliks enhance contaminant mobilization

Trace metal elements, black carbon, and other by-products of fossil fuel combustion have been continuously
 145 introduced into Arctic permafrost environments since the beginning of the industrial age (Miner et al., 2021). These contaminants may come from local sources across permafrost Arctic regions where approximately 4,500 industrial sites actively handle or store potentially hazardous substances, with an estimated 13,000–20,000 additional contaminated sites associated with this infrastructure (Langer et al., 2023), highlighting the importance of collaboration with industry. Human infrastructure can further promote talik formation by disturbing the surface energy budget (e.g., vegetation removal and replacement by gravel or tarmac) and generating localized heat, for
 150 example through oxidation of coal waste or decomposition within municipal solid waste sites (Schoolmeester et al., 2023). As permafrost thaws beneath such installations, taliks develop under the waste, creating permeable, year-round unfrozen zones that facilitate contaminant leakage into surrounding soils and waters (Langer et al., 2023). Lateral and open taliks therefore act as efficient hydrological conduits, enhancing the transfer of
 155 contaminants and linking terrestrial sources to lakes, rivers, and ultimately the coastal ocean.

In coastal ecosystems, the presence of open taliks or cryopegs (i.e., perennially cryotic solute-rich groundwater; Lewkowicz et al., 2025) may lead to the release of Na⁺ into the soil system producing locally salinized or sodic soil (Bogatova et al., 2021; Kokelj et al., 2002). As a result, high levels of Na⁺ can be toxic to plants or lead to the development of adapted plant communities.

160 4. Ongoing challenges in talik research: testable hypotheses

Investigating the biogeochemical implications of talik presence presents several ongoing challenges that motivate testable hypotheses, including the transient nature of taliks in time (H1), the need to combine multiple complementary detection approaches (H2), and the need for year-round monitoring (H3).



H1 : Talik formation can be intermittent over annual to decadal timescales

165 Talik development typically proceeds through an initial intermittent phase, during which the ground periodically refreezes depending on the year-to-year thaw–freeze balance (Farquharson et al., 2022), interrupting or resetting the biogeochemical reactions sustained during their unfrozen phase. As a result, a single point-in-time sampling campaign may fail to capture whether a given talik is actively forming, refreezing, or already stabilized, making its biogeochemical processes difficult to study without repeated or long-term observation.

170 H2 : Hydrology controls biogeochemical processes in taliks

The presence of unfrozen ground alone does not necessarily imply biogeochemical connectivity. To induce lateral transfer of nutrients, unfrozen conditions within taliks must be coupled with water movement, which depends on the hydraulic connectivity (Ebel et al., 2019). Characterizing taliks therefore requires studies on their physical and hydrological properties, and their biogeochemical functioning. Talik investigations rely on thermal (e.g., borehole
 175 temperature measurements), mechanical (e.g., probing and coring) and geophysical (e.g., ground penetrating radar and electrical resistivity tomography) measurements, as well as numerical modeling (O'Neill et al., 2020). These methods have been developed and refined specifically to detect and characterize taliks physically; none was designed to capture the biogeochemical reactions that taliks may sustain, leaving this dimension entirely unaddressed by current detection frameworks. Each method provides different information on the nature of taliks,
 180 so the use of multiple techniques enables more comprehensive investigations. For instance, long-term point measurements, such as thermistor strings in boreholes, provide crucial continuous temporal data on thermal state, whereas geophysical surveys offer valuable spatially-distributed snapshots of subsurface structure, though often limited in their temporal frequency. Talik field identification and numerical simulation methods are rapidly developing, with their own advantages and shortcomings (Wang & Niu, 2024): geophysical methods, for example,
 185 are non-destructive and suited to repeated monitoring (O'Neill et al., 2020), but do not provide direct information on pore-water chemistry or biogeochemical reactions without direct soil solution sampling. Critically, biogeochemical investigations must therefore be explicitly coupled with these approaches, as taliks fundamentally alter reaction pathways and subsurface connectivity that govern the mobilization and transport of nutrients and contaminants.

190 H3 : Supra-permafrost taliks cannot be detected in summer but play a key role in winter

Continuous monitoring is essential for capturing year-round talik dynamics. While intra-permafrost taliks can be easily identified throughout the year due to the presence of permafrost on all sides, supra-permafrost talik presence can be unambiguously identified only during winter, when the overlying seasonally frozen layer is fully frozen and unfrozen talik zones below can be clearly distinguished. However, data acquisition remains challenging: while
 195 autonomous sensors (e.g., thermistors) provide year-round thermal data, direct biogeochemical sampling requires manual intervention, which is severely restricted by extreme winter conditions and the common scientific assumption of minimal winter biological activity (Olsson et al., 2003; Shogren et al., 2020). Consequently, studies on supra-permafrost talik biogeochemistry often rely on spring freshet observations (Kelley et al., 2025). During this period, increased ground heat flux prior to snowmelt raises near-surface soil temperatures above 0°C, without
 200 requiring full active-layer thaw (Hirst et al., 2023). Meltwater infiltration, depending on hydraulic conductivity and pore water pressure (Connon et al., 2018; Schwab et al., 2020; Walvoord et al., 2019), can then activate



hydrologically connected lateral taliks, establishing hydrological pathways and mobilizing DOC and nutrients already stored within taliks to streams, lakes, and other surface waters. However, these early-season chemical signals may also reflect near-surface or lateral flow paths unrelated to talik-specific reactions. Moreover, observations from a single year cannot necessarily be extrapolated to other periods, as the rate of sub-aerial talik thickness growth can vary substantially (Farquharson et al., 2022). The critical unknown is the location of sub-aerial taliks, which depends on drivers of talik formation that are either currently evolving, such as surface disturbances (e.g., wildfire, vegetation change and human infrastructures; Holloway et al., 2020; Rey et al., 2020; Schoolmeester et al., 2023) and climate, or poorly constrained factors, such as ground ice content (Liu et al., 2022). As the lateral connectivity of these sub-aerial taliks may expand more rapidly than thermokarst features, they will exert a disproportionate influence on the permafrost carbon feedback in the coming century (Nicolsky et al., 2017).

Taken together, the three testable hypotheses have important implications for our ability to represent talik processes in models. Existing models of winter carbon emissions from high-latitude soils do not explicitly represent talik formation, as this is a small-scale process (Natali et al., 2019). As a result, the talik-specific contribution to winter carbon emissions has not yet been quantitatively isolated from that of other unfrozen microsites. However, Arctic-scale models are starting to be developed to simulate talik formation and associated carbon emissions (Parazoo et al., 2018). The road map outlined below, spanning targeted winter sampling, standardized protocols, pan-Arctic mapping, and community-building, aims to address the limitations highlighted by the three testable hypotheses and provide the empirical constraints the models currently lack.

220 **5. A road map for talik biogeochemistry research**

Taliks are emerging as critical yet understudied components of biogeochemical processes in permafrost landscapes. Understanding their full significance for carbon dynamics, nutrient and contaminant mobilization will require a coordinated, interdisciplinary effort. The three testable hypotheses outlined above provide a basis for defining priorities to advance talik biogeochemistry research. We identify four priorities: closing the seasonal gap through targeted winter and year-round sampling campaigns; standardizing protocols that make data comparable across sites and regions; mapping talik distribution; and building the international, cross-disciplinary community that can hold all of this together (Fig. 3).

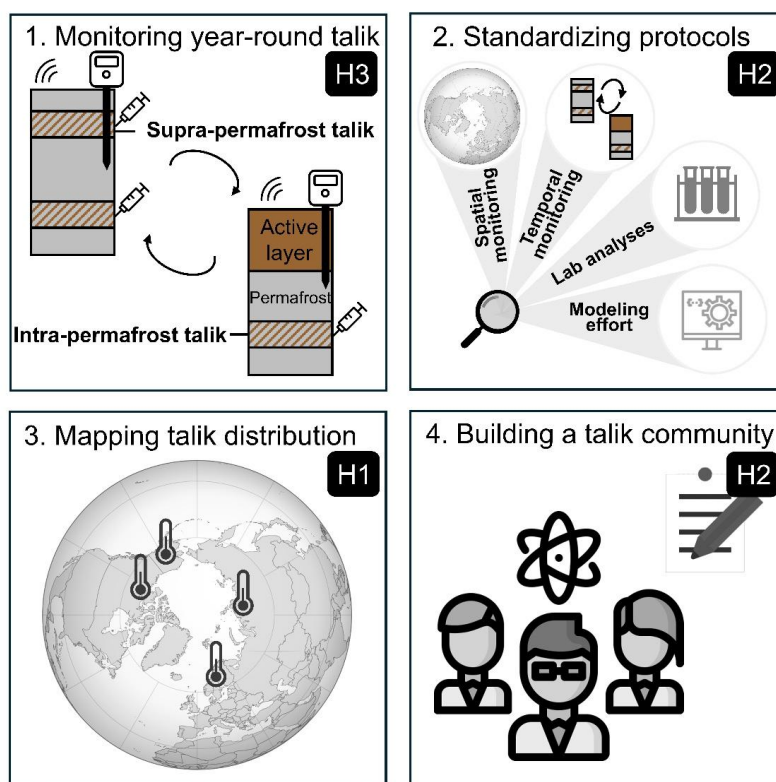


Figure 3 : A four-point road map for advancing talik biogeochemistry research, addressing the three testable hypotheses (H1, H2, and H3) outlined in Section 4. Priority 1 involves year-round monitoring with target on winter sampling campaigns, accessing both supra-permafrost and intra-permafrost taliks. Priority 2 involves standardized protocols across four axes (spatial monitoring, temporal monitoring, laboratory analyses, and modeling effort) to ensure that data collected across sites and seasons can be meaningfully compared. Priority 3 involves mapping talik distribution at the pan-Arctic scale by compiling ground temperature records from existing sensor networks across Arctic and sub-Arctic study sites. Priority 4 involves building an international, interdisciplinary talik research community to coordinate efforts and share findings.

5.1. Year-round monitoring and winter sampling campaigns

In the future, targeted winter field campaigns are critical for directly capturing biogeochemical processes operating within supra-permafrost taliks (related to H3). This is needed to quantify carbon that is transported during the winter and that could be emitted as greenhouse gases. These winter measurements will also provide critical data to constrain and validate models estimating talik contributions to carbon emissions, which currently lack observational input during this season. Current detection methods (including thermal, mechanical, and geophysical methods) now enable the precise identification of talik locations (O'Neill et al., 2020), allowing sampling efforts to be strategically focused. Conducting winter sampling in Arctic environments requires careful logistical preparation (Fig. 4). Priority measurements should include dissolved gas (CO_2 , CH_4), nutrient, DOC, and trace



element (e.g., contaminants) concentrations, and microbial diversity, together providing a first quantitative picture of winter biogeochemical processes within taliks. Beyond porewater extraction, several complementary approaches could advance *in situ* and experimental characterization of talik biogeochemistry. For example, permanently installed gas wells would allow continuous, non-destructive monitoring of gas emissions (CO₂, CH₄), capturing transient taliks that single sampling campaigns cannot resolve (Voigt et al., 2019). Next-generation incubation facilities, such as the Deep Soil Ecotron (Stokstad, 2021), which enables controlled manipulation of soil profiles under realistic thermal and hydrological gradients, could simulate different talik configurations (closed, isolated, lateral) and test how hydrological connectivity governs biogeochemical reaction rates under controlled conditions.



Figure 4: Winter field access to supra-permafrost taliks using motorized drilling systems at Eight Mile Lake, Alaska (USA). Drilling through the seasonally frozen active layer is required to access unfrozen talik soils, where pore waters remain liquid year-round beneath the frozen surface. Talik soils are collected and placed into plastic bags, using insulated processing to prevent rapid freezing upon exposure and pore waters are subsequently extracted using Rhizon samplers. This approach enables direct biogeochemical sampling during the winter months, the season when taliks are most clearly distinguished from surrounding frozen ground. The authors have obtained written consent to publish the image.

5.2. Standardized protocols for cross-study comparison

As talik research expands, inconsistent sampling and analytical methods risk producing datasets that cannot be meaningfully compared. Agreeing on standardized laboratory protocols for pore water chemistry, for example, and field sampling procedures, is essential for building a coherent, cumulative body of knowledge.



Isotope tracers such as silicon isotopes are known to be sensitive to freeze–thaw cycling in permafrost regions and offer particular promise (Hirst et al., 2023; Villani et al., 2025). But the value of such tools depends entirely on their consistent application across sites. The SPLASH initiative (Standardized Methods across Permafrost Landscapes: from Arctic Soils to Hydrosystems) provides an inspiring model (Bouchard et al., 2020): a community-driven framework to harmonize field strategies across landscape types, seasons, and regions. A talik-focused extension of this approach, bringing together geophysicists, hydrologists, geochemists, and microbiologists around shared protocols, would be transformative (related to H2).

5.3. Mapping talik distribution at the pan-Arctic scale

A fundamental obstacle to understanding talik biogeochemistry is that the distribution of the different talik types remains poorly known. Without a reliable, circumpolar picture of talik distribution, upscaling any local measurement remains speculative. Land surface models such as CLM4.5 offer a starting point for mapping talik distribution as they capture permafrost thermal and hydrological states (Lawrence & Slater, 2008; Parazoo et al., 2018). These models could be further refined to explicitly simulate talik-driven carbon emissions if informed by the pan-Arctic inventory and standardized field data proposed here.

Critically, taliks can be intermittent, appearing and disappearing across years, making long-term monitoring essential alongside modeling efforts (related to H1). One promising approach is to take advantage of the dense network of ground-temperature sensors already deployed at Arctic study sites. By gathering soil temperature data across hundreds of Arctic study sites, as was already done with ~54 sites to detect talik formation (Farquharson et al., 2022), the research community could build the first pan-Arctic inventory of talik occurrence. This would transform our capacity to locate taliks and prioritize biogeochemical investigation where it matters most. Following the model of the Circumpolar Active Layer Monitoring (CALM) program (Nelson et al., 2021), which has successfully harmonized active layer thickness data across the Arctic, a coordinated effort to compile and share soil temperature records could enable pan-Arctic identification of talik occurrence at unprecedented scale. A first step would be to establish a minimum data standard, continuous soil temperature records at depth, with at least two years of coverage, and to create an open repository where existing borehole datasets can be contributed and quality-controlled, following the data harmonization principles of the CALM program. Such an effort would not require new infrastructure: it would mobilize data that already exist but remain scattered across national programs and individual research groups. Realizing this potential will require close collaboration between field scientists collecting and curating these ground temperature records and modelers integrating them into land surface models, ensuring that the resulting pan-Arctic inventory directly feeds into improved simulations of talik-driven carbon emissions.

5.4. Building an international talik research community

Ultimately, progress on the above priorities depends on people working together across disciplines and borders. Talik biogeochemistry sits at the intersection of geophysics, hydrology, geochemistry, microbiology, climate modeling, and industry (related to H2). The field needs dedicated spaces for knowledge exchange: regular workshops, international working groups, and community surveys that minimize redundancy and accelerate synthesis.



Existing structures offer ready templates. The IPA action groups provide successful examples (Bouchard et al., 2020; Strauss et al., 2021), and demonstrate how focused, community-led efforts can mobilize expertise and produce high-impact outputs. Another example is the Permafrost Carbon Network which, with over 500 members across 130 institutions in 21 countries, shows the scale that is achievable. A dedicated talik working group could serve three functions: maintaining a shared database of talik locations and physical properties; coordinating joint winter field campaigns across multiple sites and countries; and producing community-agreed protocols for biogeochemical sampling. Community surveys, analogous to permaCOST (a coordinated European effort to harmonize permafrost monitoring and data comparability; permacost.eu), would provide baseline inventories of ongoing talik research globally, mapping who is working where and on what, preventing duplication and identifying geographical gaps.

Taliks are not a niche concern. They are windows into a permafrost system in transition, and understanding what flows through them (including carbon, nutrients, and contaminants) is essential for projecting the Arctic's role in the Earth system. What is now required is a collective commitment to pursue these efforts.

Acknowledgments

We acknowledge funding from the Fonds National de la Recherche Scientifique to S.O. and M.V. (FNRS: FC69480 and FC49507).

Author Contributions

M.V. and S.O. wrote the original draft of the manuscript. L.M.F. and V.E.R. provided feedback on the manuscript. All authors contributed to the discussions and revisions of the manuscript. All authors have read and approved the manuscript.

Competing interests

The authors declare no competing financial or non-financial interests.

References

- Bergman, O. (ORCID:0009000263063562), Walter_Anthony, K., Eliani-Russak, E., & Sivan, O. (2025). Nitrogen Redox Controls on Greenhouse Gas Production in Yedoma Taliks. *Global Change Biology*, 31(7). <https://doi.org/10.1111/gcb.70356>
- Bogatova, D., Buldovich, S., & Khilimonyuk, V. (2021). Snow Patches and Their Influence on Coastal Erosion at Baydaratskaya Bay Coast, Kara Sea, Russian Arctic. *Water*, 13(10), Article 10. <https://doi.org/10.3390/w13101432>
- Bouchard, F., Agnan, Y., Bröder, L., Fouché, J., Hirst, C., & Sjöberg, Y. (2020). The SPLASH Action Group – Towards standardized sampling strategies in permafrost science. *Advances in polar science*, 31(3). <https://doi.org/10.13679/j.advps.2020.0009>
- Bowen, J. C., Ward, C. P., Kling, G. W., & Cory, R. M. (2020). Arctic Amplification of Global Warming Strengthened by Sunlight Oxidation of Permafrost Carbon to CO₂. *Geophysical Research Letters*, 47(12), e2020GL087085. <https://doi.org/10.1029/2020GL087085>



- Connon, R., Devoie, É., Hayashi, M., Veness, T., & Quinton, W. (2018). The Influence of Shallow Taliks on Permafrost Thaw and Active Layer Dynamics in Subarctic Canada. *Journal of Geophysical Research: Earth Surface*, 123(2), 281-297. <https://doi.org/10.1002/2017JF004469>
- 345 Devoie, É., Connon, R. F., Beddoe, R., Goordial, J., Quinton, W. L., & Craig, J. R. (2024). Disconnected active layers and unfrozen permafrost : A discussion of permafrost-related terms and definitions. *Science of The Total Environment*, 912, 169017. <https://doi.org/10.1016/j.scitotenv.2023.169017>
- Devoie, É. G., Craig, J. R., Connon, R. F., & Quinton, W. L. (2019). Taliks : A Tipping Point in Discontinuous Permafrost Degradation in Peatlands. *Water Resources Research*, 55(11), 9838-9857. <https://doi.org/10.1029/2018WR024488>
- 350 Ebel, B. A., Koch, J. C., & Walvoord, M. A. (2019). Soil Physical, Hydraulic, and Thermal Properties in Interior Alaska, USA : Implications for Hydrologic Response to Thawing Permafrost Conditions. *Water Resources Research*, 55(5), 4427-4447. <https://doi.org/10.1029/2018WR023673>
- Farquharson, L. M., Romanovsky, V. E., Kholodov, A., & Nicolsky, D. (2022). Sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska. *Nature Geoscience*, 15(6), Article 6. <https://doi.org/10.1038/s41561-022-00952-z>
- 355 Grogan, P., & Chapin III, F. S. (1999). Arctic Soil Respiration : Effects of Climate and Vegetation Depend on Season. *Ecosystems*, 2(5), 451-459. <https://doi.org/10.1007/s100219900093>
- Herndon, E., Kinsman-Costello, L., & Godsey, S. (2020). Biogeochemical Cycling of Redox-Sensitive Elements in Permafrost-Affected Ecosystems. In K. Dontsova, Z. Balogh-Brunstad, & G. Le Roux (Éds.), *Geophysical Monograph Series* (1^{re} éd., p. 245-265). <https://doi.org/10.1002/9781119413332.ch12>
- 360 Heslop, J. K., Walter Anthony, K. M., Grosse, G., Liebner, S., & Winkel, M. (2019). Century-scale time since permafrost thaw affects temperature sensitivity of net methane production in thermokarst-lake and talik sediments. *Science of The Total Environment*, 691, 124-134. <https://doi.org/10.1016/j.scitotenv.2019.06.402>
- 365 Heslop, J. K., Walter Anthony, K. M., Sepulveda-Jauregui, A., Martinez-Cruz, K., Bondurant, A., Grosse, G., & Jones, M. C. (2015). Thermokarst lake methanogenesis along a complete talik profile. *Biogeosciences*, 12(14), 4317-4331. <https://doi.org/10.5194/bg-12-4317-2015>
- Heslop, J. K., Winkel, M., Walter Anthony, K. M., Spencer, R. G. M., Podgorski, D. C., Zito, P., Kholodov, A., Zhang, M., & Liebner, S. (2019). Increasing Organic Carbon Biolability With Depth in Yedoma Permafrost : Ramifications for Future Climate Change. *Journal of Geophysical Research: Biogeosciences*, 124(7), 2021-2038. <https://doi.org/10.1029/2018JG004712>
- 370 Hirst, C., Mauclet, E., Monhonval, A., Tihon, E., Ledman, J., Schuur, E. A. G., & Opfergelt, S. (2022). Seasonal changes in hydrology and permafrost degradation control mineral element-bound DOC transport from permafrost soils to streams. *Global Biogeochemical Cycles*. <https://doi.org/10.1029/2021GB007105>
- 375 Hirst, C., Monhonval, A., Mauclet, E., Thomas, M., Villani, M., Ledman, J., Schuur, E. A. G., & Opfergelt, S. (2023). Evidence for late winter biogeochemical connectivity in permafrost soils. *Communications Earth & Environment*, 4(1), Article 1. <https://doi.org/10.1038/s43247-023-00740-6>
- 380 Holloway, J. E., Lewkowicz, A. G., Douglas, T. A., Li, X., Turetsky, M. R., Baltzer, J. L., & Jin, H. (2020). Impact of wildfire on permafrost landscapes : A review of recent advances and future prospects. *Permafrost and Periglacial Processes*, 31(3), 371-382. <https://doi.org/10.1002/ppp.2048>
- Jansson, J. K., & Taş, N. (2014). The microbial ecology of permafrost. *Nature Reviews Microbiology*, 12(6), 414-425. <https://doi.org/10.1038/nrmicro3262>
- 385 Kelley, A. K., Axler, Z., Ledman, J., De La Torre, M., Ebert, C. H., Springer, A. E., Kaufman, D. S., & Schuur, E. A. G. (2025). Lateral Dissolved Organic Carbon Losses Represent ~10% of Upland Tundra Carbon Losses and Include Seasonal Permafrost Contributions. *Journal of Geophysical Research: Biogeosciences*, 130(11), e2025JG009067. <https://doi.org/10.1029/2025JG009067>
- Kelley, A. K., Hirst, C., Ebert, C. H., Axler, Z., Ledman, J., Opfergelt, S., & Schuur, E. A. G. (2026). Permafrost thaw exposes old dissolved organic carbon to photo- and biodegradation. *Environmental Research: Ecology*, 5(1), 015003. <https://doi.org/10.1088/2752-664X/ae45af>
- 390 Kokelj, S. V., Smith, C. A. S., & Burn, C. R. (2002). Physical and chemical characteristics of the active layer and permafrost, Herschel Island, western Arctic Coast, Canada. *Permafrost and Periglacial Processes*, 13(2), 171-185. <https://doi.org/10.1002/ppp.417>



- 395 Kurylyk, B. L., & Walvoord, M. A. (2021). Permafrost Hydrogeology. In D. Yang & D. L. Kane (Éds.), *Arctic Hydrology, Permafrost and Ecosystems* (p. 493-523). Springer International Publishing.
https://doi.org/10.1007/978-3-030-50930-9_17
- Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L., & Zipper, S. C. (2018). Changing groundwater discharge dynamics in permafrost regions. *Environmental Research Letters*, 13(8), 084017.
<https://doi.org/10.1088/1748-9326/aad404>
- 400 Langer, M., von Deimling, T. S., Westermann, S., Rolph, R., Rutte, R., Antonova, S., Rachold, V., Schultz, M., Oehme, A., & Grosse, G. (2023). Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. *Nature Communications*, 14(1), 1721.
<https://doi.org/10.1038/s41467-023-37276-4>
- 405 Lawrence, D. M., & Slater, A. G. (2008). Incorporating organic soil into a global climate model. *Climate Dynamics*, 30(2-3), 145-160. <https://doi.org/10.1007/s00382-007-0278-1>
- Lewkowicz, A. G., O'Neill, H. B., Wolfe, S. A., Roy-Leveillee, P., Roujanski, V., Hoeve, E., Gruber, S., Brooks, H., Rudy, A. C. A., Koenig, C. E. M., Brown, N., & Bonnaventure, P. P. (2025). *Glossary of Permafrost Science and Engineering. Permafrost Terminology Action Group Canadian Permafrost Association*.
- 410 Lewkowicz, A. G., Wolfe, S. A., Roujanski, V. E., Hoeve, E., O'Neill, H. B., Gruber, S., Roy-Leveillee, P., Brown, N., Koenig, C. E. M., Brooks, H., Rudy, A. C. A., Bonnaventure, P. P., & Paquette, M. (2024). *An Illustrated Permafrost Dictionary*. <https://ostrnrcan-dostnrcan.canada.ca/handle/1845/347162>
- Liljedahl, A. K., Timling, I., Frost, G. V., & Daanen, R. P. (2020). Arctic riparian shrub expansion indicates a shift from streams gaining water to those that lose flow. *Communications Earth & Environment*, 1(1), 50. <https://doi.org/10.1038/s43247-020-00050-1>
- 415 Liu, W., Fortier, R., Molson, J., & Lemieux, J.-M. (2021). A conceptual model for talik dynamics and icing formation in a river floodplain in the continuous permafrost zone at Salluit, Nunavik (Quebec), Canada. *Permafrost and Periglacial Processes*, 32(3), 468-483. <https://doi.org/10.1002/ppp.2111>
- Liu, W., Fortier, R., Molson, J., & Lemieux, J.-M. (2022). Three-Dimensional Numerical Modeling of Cryo-Hydrogeological Processes in a River-Talik System in a Continuous Permafrost Environment. *Water Resources Research*, 58(3), e2021WR031630. <https://doi.org/10.1029/2021WR031630>
- 420 Luo, D., Liu, J., Chen, F., & Li, S. (2025). Observed talik development triggers a tipping point in marginal permafrost of the Qinghai-Xizang Plateau. *Geoscience Frontiers*, 16(5), 102122.
<https://doi.org/10.1016/j.gsf.2025.102122>
- 425 Ma, Q., Jin, H., Yu, C., & Bense, V. F. (2019). Dissolved organic carbon in permafrost regions : A review. *Science China Earth Sciences*, 62(2), 349-364. <https://doi.org/10.1007/s11430-018-9309-6>
- Meisel, O. H., Dean, J. F., Vonk, J. E., Wacker, L., Reichart, G.-J., & Dolman, H. (2021). Porewater $\delta^{13}\text{C}_{\text{DOC}}$ indicates variable extent of degradation in different talik layers of coastal Alaskan thermokarst lakes. *Biogeosciences*, 18(7), 2241-2258. <https://doi.org/10.5194/bg-18-2241-2021>
- 430 Millero, F. J., Feistel, R., Wright, D. G., & McDougall, T. J. (2008). The composition of Standard Seawater and the definition of the Reference-Composition Salinity Scale. *Deep Sea Research Part I: Oceanographic Research Papers*, 55(1), 50-72. <https://doi.org/10.1016/j.dsr.2007.10.001>
- Miner, K. R., D'Andrilli, J., Mackelprang, R., Edwards, A., Malaska, M. J., Waldrop, M. P., & Miller, C. E. (2021). Emergent biogeochemical risks from Arctic permafrost degradation. *Nature Climate Change*, 11(10), 809-819. <https://doi.org/10.1038/s41558-021-01162-y>
- 435 Natali, S. M., Watts, J. D., Rogers, B. M., Potter, S., Ludwig, S. M., Selbmann, A.-K., Sullivan, P. F., Abbott, B. W., Arndt, K. A., Birch, L., Björkman, M. P., Bloom, A. A., Celis, G., Christensen, T. R., Christiansen, C. T., Commene, R., Cooper, E. J., Crill, P., Czimczik, C., ... Zona, D. (2019). Large loss of CO₂ in winter observed across the northern permafrost region. *Nature Climate Change*, 9(11), 852-857.
<https://doi.org/10.1038/s41558-019-0592-8>
- 440 Nelson, F. E., Shiklomanov, N. I., & Nyland, K. E. (2021). Cool, CALM, collected : The Circumpolar Active Layer Monitoring program and network. *Polar Geography*, 44(3), 155-166.
<https://doi.org/10.1080/1088937X.2021.1988001>
- Nicolosky, D. J., Romanovsky, V. E., Panda, S. K., Marchenko, S. S., & Muskett, R. R. (2017). Applicability of the ecosystem type approach to model permafrost dynamics across the Alaska North Slope. *Journal of Geophysical Research: Earth Surface*, 122(1), 50-75. <https://doi.org/10.1002/2016JF003852>
- 445



- Olsson, P. Q., Sturm, M., Racine, C. H., Romanovsky, V., & Liston, G. E. (2003). Five Stages of the Alaskan Arctic Cold Season with Ecosystem Implications. *Arctic, Antarctic, and Alpine Research*, 35(1), 74-81. [https://doi.org/10.1657/1523-0430\(2003\)035%5B0074:FSOTAA%5D2.0.CO;2](https://doi.org/10.1657/1523-0430(2003)035%5B0074:FSOTAA%5D2.0.CO;2)
- 450 O'Neill, H. B., Roy-Leveille, P., Lebedeva, L., & Ling, F. (2020). Recent advances (2010–2019) in the study of taliks. *Permafrost and Periglacial Processes*, 31(3), 346-357. <https://doi.org/10.1002/ppp.2050>
- Opfergelt, S. (2020). The next generation of climate model should account for the evolution of mineral-organic interactions with permafrost thaw. *Environmental Research Letters*, 15(9), 091003. <https://doi.org/10.1088/1748-9326/ab9a6d>
- 455 Parazoo, N. C., Koven, C. D., Lawrence, D. M., Romanovsky, V., & Miller, C. E. (2018). Detecting the permafrost carbon feedback : Talik formation and increased cold-season respiration as precursors to sink-to-source transitions. *The Cryosphere*, 12(1), 123-144. <https://doi.org/10.5194/tc-12-123-2018>
- Patzner, M. S., Kainz, N., Lundin, E., Barczok, M., Smith, C., Herndon, E., Kinsman-Costello, L., Fischer, S., Straub, D., Kleindienst, S., Kappler, A., & Bryce, C. (2022). Seasonal Fluctuations in Iron Cycling in Thawing Permafrost Peatlands. *Environmental Science & Technology*, 56(7), 4620-4631. <https://doi.org/10.1021/acs.est.1c06937>
- 460 Plaza, C., Pegoraro, E., Bracho, R., Celis, G., Crummer, K. G., Hutchings, J. A., Hicks Pries, C. E., Mauritz, M., Natali, S. M., Salmon, V. G., Schädel, C., Webb, E. E., & Schuur, E. A. G. (2019). Direct observation of permafrost degradation and rapid soil carbon loss in tundra. *Nature Geoscience*, 12(8), 627-631. <https://doi.org/10.1038/s41561-019-0387-6>
- 465 Quinton, W., Berg, A., Braverman, M., Carpino, O., Chasmer, L., Connon, R., Craig, J., Devoie, É., Hayashi, M., Haynes, K., Olefeldt, D., Pietroniro, A., Rezanezhad, F., Schincariol, R., & Sonnentag, O. (2019). A synthesis of three decades of hydrological research at Scotty Creek, NWT, Canada. *Hydrology and Earth System Sciences*, 23(4), 2015-2039. <https://doi.org/10.5194/hess-23-2015-2019>
- 470 Rangel, R. C., Parsekian, A. D., Farquharson, L. M., Jones, B. M., Ohara, N., Creighton, A. L., Gaglioti, B. V., Kanevskiy, M., Breen, A. L., Bergstedt, H., Romanovsky, V. E., & Hinkel, K. M. (2021). Geophysical Observations of Taliks Below Drained Lake Basins on the Arctic Coastal Plain of Alaska. *Journal of Geophysical Research: Solid Earth*, 126(3), e2020JB020889. <https://doi.org/10.1029/2020JB020889>
- Rey, D. M., Walvoord, M. A., Minsley, B. J., Ebel, B. A., Voss, C. I., & Singha, K. (2020). Wildfire-Initiated Talik Development Exceeds Current Thaw Projections : Observations and Models From Alaska's Continuous Permafrost Zone. *Geophysical Research Letters*, 47(15), e2020GL087565. <https://doi.org/10.1029/2020GL087565>
- 475 Roux, P., Hirst, C., Villani, M., du Bois d'Aische, E., Osy, C., Kelley, A. K., Ledman, J., Schuur, E. A. G., & Opfergelt, S. (2026). Radiogenic Sr isotopes reveal extended seasonal windows of soil-river dissolved organic carbon transfer in an Arctic permafrost catchment. *Chemical Geology*, 712, 123427. <https://doi.org/10.1016/j.chemgeo.2026.123427>
- 480 Schoolmeester, T., Sinisalo, A., Alfthan, B., Luigi, G. D., Westerveld, L., Mulelid, O. B., Sevaldsen, P., Kurvits, T., & Eckhoff, T. S. (2023). *Arctic Permafrost Atlas*. <https://policycommons.net/artifacts/6950321/arctic-permafrost-atlas/7860371/>
- 485 Schuur, E. A. G., Abbott, B. W., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., Grosse, G., Jones, M., Koven, C., Leshyk, V., Lawrence, D., Lorant, M. M., Mauritz, M., Olefeldt, D., Natali, S., Rodenhizer, H., Salmon, V., Schädel, C., Strauss, J., ... Turetsky, M. (2022). Permafrost and Climate Change : Carbon Cycle Feedbacks From the Warming Arctic. *Annual Review of Environment and Resources*, 47(1), 343-371. <https://doi.org/10.1146/annurev-environ-012220-011847>
- 490 Schwab, M. S., Hilton, R. G., Raymond, P. A., Haghipour, N., Amos, E., Tank, S. E., Holmes, R. M., Tipper, E. T., & Eglinton, T. I. (2020). An Abrupt Aging of Dissolved Organic Carbon in Large Arctic Rivers. *Geophysical Research Letters*, 47(23), e2020GL088823. <https://doi.org/10.1029/2020GL088823>
- Shogren, A. J., Zarnetske, J. P., Abbott, B. W., Iannucci, F., & Bowden, W. B. (2020). We cannot shrug off the shoulder seasons : Addressing knowledge and data gaps in an Arctic headwater. *Environmental Research Letters*, 15(10), 104027. <https://doi.org/10.1088/1748-9326/ab9d3c>
- 495 Stokstad, E. (2021). New observatory to bring soil up from the deep. *Science*, 374(6565), 250.
- Strauss, J., Fuchs, M., Hugelius, G., Miesner, F., Nitze, I., Opfergelt, S., Schuur, E., Treat, C., Turetsky, M., Yang, Y., & Grosse, G. (2025). Organic matter storage and vulnerability in the permafrost domain. In S.



- 500 Elias (Éd.), *Encyclopedia of Quaternary Science (Third edition)* (p. 399-410). Elsevier.
<https://doi.org/10.1016/B978-0-323-99931-1.00164-1>
- Strauss, J., Laboor, S., Schirrmeister, L., Fedorov, A. N., Fortier, D., Froese, D., Fuchs, M., Günther, F.,
 Grigoriev, M., Harden, J., Hugelius, G., Jongejans, L. L., Kanevskiy, M., Kholodov, A., Kunitsky, V.,
 Kraev, G., Lozhkin, A., Rivkina, E., Shur, Y., ... Grosse, G. (2021). Circum-Arctic Map of the Yedoma
 Permafrost Domain. *Frontiers in Earth Science*, 9. <https://doi.org/10.3389/feart.2021.758360>
- 505 Villani, M., Hirst, C., du Bois d'Aische, E., Thomas, M., Opfergelt, S., Lundin, E., Giesler, R., & Mu00f0rth, C.-
 M. (2025). Lengthening of biogeochemical processes during winter in degraded permafrost soils.
Geochemical Perspectives Letters, 34(34), 36-42.
- Voggenreiter, E., ThomasArrigo, L., Bottaro, M., Kilian, J., Straub, D., Ring-Hrubesh, F., Bryce, C., Stahl, M.,
 Kappler, A., & Joshi, P. (2025). Suppression of Methanogenesis by Microbial Reduction of Iron-
 Organic Carbon Associations in Fully Thawed Permafrost Soil. *Journal of Geophysical Research:*
 510 *Biogeosciences*, 130(3), e2024JG008650. <https://doi.org/10.1029/2024JG008650>
- Voigt, C., Marushchak, M. E., Mastepanov, M., Lamprecht, R. E., Christensen, T. R., Dorodnikov, M.,
 Jackowicz-Korczyński, M., Lindgren, A., Lohila, A., Nykänen, H., Oinonen, M., Oksanen, T., Palonen,
 V., Treat, C. C., Martikainen, P. J., & Biasi, C. (2019). Ecosystem carbon response of an Arctic peatland
 515 to simulated permafrost thaw. *Global Change Biology*, 25(5), 1746-1764.
<https://doi.org/10.1111/gcb.14574>
- Walter Anthony, K. M., Anthony, P., Hasson, N., Edgar, C., Sivan, O., Eliani-Russak, E., Bergman, O., Minsley,
 B. J., James, S. R., Pastick, N. J., Kholodov, A., Zimov, S., Euskirchen, E., Bret-Harte, M. S., Grosse,
 G., Langer, M., & Nitzbon, J. (2024). Upland Yedoma taliks are an unpredicted source of atmospheric
 520 methane. *Nature Communications*, 15(1), 6056. <https://doi.org/10.1038/s41467-024-50346-5>
- Walvoord, M. A., & Striegl, R. G. (2007). Increased groundwater to stream discharge from permafrost thawing
 in the Yukon River basin : Potential impacts on lateral export of carbon and nitrogen. *Geophysical*
Research Letters, 34(12). <https://doi.org/10.1029/2007GL030216>
- Walvoord, M. A., Voss, C. I., Ebel, B. A., & Minsley, B. J. (2019). Development of perennial thaw zones in
 525 boreal hillslopes enhances potential mobilization of permafrost carbon. *Environmental Research*
Letters, 14(1), 015003. <https://doi.org/10.1088/1748-9326/aaf0cc>
- Walvoord, M. A., Voss, C. I., & Wellman, T. P. (2012). Influence of permafrost distribution on groundwater flow
 in the context of climate-driven permafrost thaw : Example from Yukon Flats Basin, Alaska, United
 States. *Water Resources Research*, 48(7). <https://doi.org/10.1029/2011WR011595>
- 530 Wang, Y., & Niu, F. (2024). Advancements in Talik Research and a Novel Approach to Treatment for Talik
 beneath Subgrade. *Journal of Cold Regions Engineering*, 38(3), 03124002.
<https://doi.org/10.1061/JCRGEI.CRENG-779>
- Wellman, T. P., Voss, C. I., & Walvoord, M. A. (2013). Impacts of climate, lake size, and supra- and sub-
 permafrost groundwater flow on lake-talik evolution, Yukon Flats, Alaska (USA). *Hydrogeology*
 535 *Journal*, 21(1), 281-298. <https://doi.org/10.1007/s10040-012-0941-4>