nature geoscience

Perspective

https://doi.org/10.1038/s41561-026-02015-z

Iron as a driver of organic carbon fate in permafrost regions

Received: 10 October 2025

Accepted: 13 May 2026

Published online: 6 July 2026

Check for updates

S. Opfergelt[1] ✉, E. M. Herndon[2], C. Bryce[3], A. J. Barker[4] & C. Hirst[5]

Iron (Fe) and its biogeochemical interactions with organic carbon (OC) exert critical controls over carbon storage and water quality across Arctic and sub-Arctic landscapes. Permafrost thaw affects Fe–organic carbon interactions by exposing thawed material and driving shifts in hydrologic regimes. Here we propose a conceptual framework describing how Fe–OC interactions respond to permafrost thaw and the implications for global carbon cycling. The framework builds on current understanding of hydrologically driven processes that are altered by permafrost thaw, including microbial Fe reduction that influences OC decomposition and carbon emissions; Fe cycling through redox transformations and sulfide oxidation; dissolution and reprecipitation of Fe–OC assemblages; and Fe export to river networks. We put forward four testable hypotheses—on topics from Fe supply to its role in soil OC storage and transfer to rivers—to advance understanding of the coupled environmental controls on pore-scale reactions (that is, microscale reactions at mineral–water–microorganism interfaces) that are central to global Fe–OC cycling. Our framework highlights how soil-profile- and landscape-scale processes, such as hydrologic connectivity and redox dynamics, regulate pore-scale Fe–OC reactions.

Permafrost regions store nearly twice the amount of carbon (C) currently present in the atmosphere and are a source of the greenhouse gases (GHGs) carbon dioxide (CO_2) and methane (CH_4)[1]. Arctic warming is driving extensive permafrost thaw, resulting in a deepening of the seasonally thawed active layer and substantial transformations in land surface hydrology[2]. These hydrological changes profoundly impact soil redox conditions, which in turn regulate biogeochemical processes within thaw-affected soils[3]. Iron (Fe), particularly in the form of ferric (Fe(III)) minerals, is among the most redox-sensitive soil constituents and plays a pivotal role in organic carbon (OC) dynamics[4]. This influence is exerted through two main pathways: (1) microbial Fe cycling, which affects C mineralization and the production of GHGs; and (2) Fe–OC interactions, which can protect OC from microbial degradation.

As permafrost thaw progresses, understanding the changing nature of Fe–OC interactions becomes critical for predicting the fate of soil OC: whether it remains stabilized, is mobilized into aquatic systems or is emitted to the atmosphere. Although factors such as the intrinsic chemical composition of organic matter, microbial activity and environmental conditions all influence OC persistence across soils, lakes, rivers and wetlands[5], a growing body of evidence underscores the central role of Fe–OC interactions in the fate of OC. The redox-sensitive nature of Fe phases causes them to transform with changes in soil moisture that are driven by rain events, snowmelt or permafrost thaw. In this Perspective, we build on emerging insights to propose a conceptual framework for how Fe–OC interactions—from microscale microbial interfaces to macroscale hydrological networks—will respond to permafrost thaw in (sub-)Arctic landscapes (Fig. 1).

Permafrost thaw alters hydrology and microbial Fe cycling

Permafrost is an impermeable barrier that restricts groundwater flow to the seasonally thawed active layer. Permafrost thaw alters hydrologic flow paths, either by increasing the active layer depth, which enhances

[1]Earth and Life Institute, UCLouvain, Louvain-la-Neuve, Belgium. [2]Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, USA. [3]School of Earth Sciences, University of Bristol, Bristol, UK. [4]Cold Regions Research and Engineering Laboratory, Fairbanks, Alaska, USA. [5]Department of Earth Sciences, Durham University, Durham, UK. ✉e-mail: sophie.opfergelt@uclouvain.be

https://doi.org/10.1038/s41561-026-02015-z

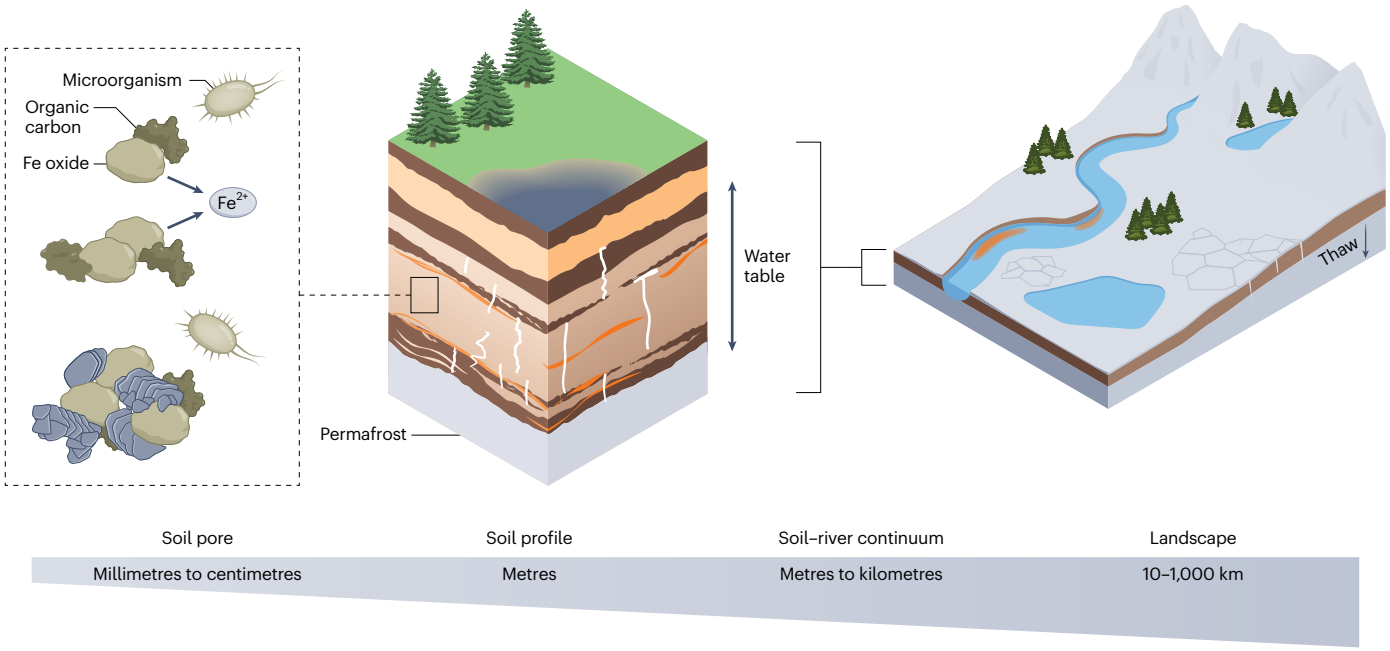

Fig. 1 | Scales of Fe–OC interactions in permafrost regions. Schematic of the different spatial scales at which Fe–OC interactions are influenced in permafrost landscapes.

Table 1 | Key research questions explored across scales—from pores to landscapes—to investigate Fe–OC interactions in permafrost regions, along with the main variables of interest and representative measurement techniques (non exhaustive)

Scale	Ongoing questions	Variables of interest	Techniques
Soil pore (millimetres to centimetres)	How do microbial processes affect Fe–OC interactions?	Genetics	Genomics[53]
		Interface localization	Electron microscopy (SEM and TEM) and XAS[54,55]
		Fe and C speciation	XAS, NMR and FT-ICR[56,57]
Soil profile (metres)	How do environmental conditions shape Fe–OC interactions in soils?	Soil pH and soil redox potential	Field monitoring in situ with probes[26,54,58]
		Microscale Fe speciation	Spectrophotometry and XAS[12,54]
		Soil-pore water chemistry	ICP-OES, ICP-MS and spectrophotometry[26,34]
		Soil chemistry and mineralogy	XRF, XRD, ICP-OES, Fe selective extractions and XAS[4,28,30,59]
		Tracing Fe–OC dissolution–reprecipitation	Radiogenic strontium isotopes[60,61]
		Soil moisture	Time domain reflectometry[62,63]
		Simulation of soil biogeochemistry	Reactive transport models[19,64]
Soil–river continuum (metres to kilometres)	Where and how are Fe and OC transported and transformed?	Fe and C concentration	ICP-OES, ICP-MS and spectrophotometry[34,65]
		Fe and C size distribution	Size separation (filtration and dialysis)[66,67]
		Fe and C morphology	Electron microscopy (SEM and TEM)[55]
		Fe sources	Fe isotopes[32,68–70]
		Type of Fe–OC in size fractions	Spectroscopy and mass spectrometry[32,70–72]
		Thaw depth and rainfall	Long-term time-series field monitoring[73]
		Light conditions	Photosynthetically active radiation[31]
Landscape (10–1,000 km)	How does landscape-scale permafrost degradation influence Fe–OC interactions?	Ground microtopography	Remote sensing: LiDAR[74]
		Soil surface temperature	Remote sensing: UAV-based thermal camera[75,76]
		Water table fluctuations	Piezometer and geophysics (GPR and ERT)[44]
		River water spectral properties	Eyes, UAV-based RGB camera and satellite imagery[38,77]
		C cycling and gas emissions	ESMs[78]

ERT, electrical resistivity tomography; FT-ICR, Fourier transform ion cyclotron resonance; GPR, ground-penetrating radar; ICP-MS, inductively coupled plasma mass spectrometry; ICP-OES, inductively coupled plasma optical emission spectrometry; LiDAR, light detection and ranging; NMR, nuclear magnetic resonance; RGB, red, green, blue; SEM, scanning electron microscopy; TEM, transmission electron microscopy; UAV, unmanned aerial vehicle; XAS, X-ray absorption spectroscopy; XRD, X-ray diffraction; XRF, X-ray fluorescence.

https://doi.org/10.1038/s41561-026-02015-z

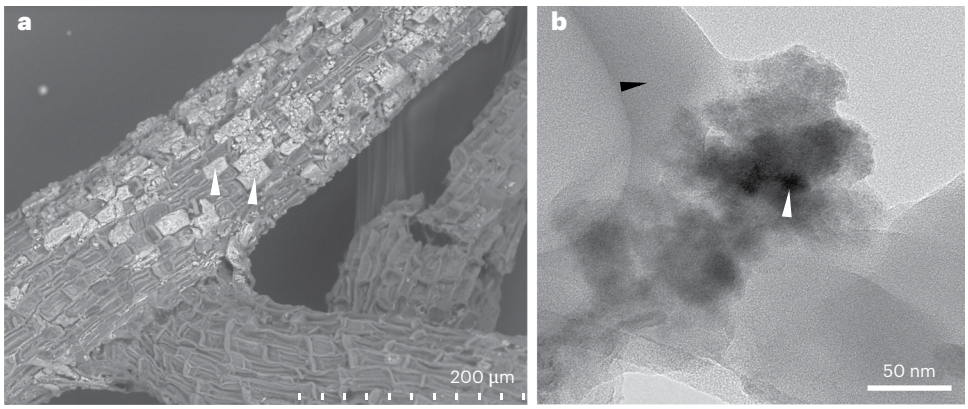

Fig. 2 | Images of Fe–OC interactions in Arctic and sub-Arctic environments. **a**, Scanning electron microscopy image of Fe oxides (white arrows) on Arctic sedge roots. **b**, Transmission electron microscopy image of short-range ordered Fe oxide (ferrihydrite; white arrow) particles attached to the OC (black arrow) surface in Arctic riverine suspended sediment. Credit: **b**, S. Shaw, I. Burke.

infiltration and results in deeper flow paths[2], or by causing ground collapse, leading to the formation of water-filled depressions[6]. These complex landscape responses to thaw propagate to subsurface redox conditions and Fe redox biogeochemistry[3] (Table 1).

Soil drainage promotes oxidizing conditions that facilitate aerobic respiration, the Fe-mediated production of reactive oxygen species that degrade organic matter[7], Fe(III) oxide formation and OC association with Fe oxides[4]. Conversely, inundation generates reducing conditions that favour anaerobic respiration pathways, including ferric Fe reduction[8,9]. Microbial respiration exists along a gradient of redox potentials between these two endmembers, and different respiration pathways often overlap in space and/or time or may even be decoupled from inundation. For example, inundated soils can maintain oxidizing conditions within porous organic layers where flow is high and where plant roots and/or algae release oxygen gas into the subsurface, leading to Fe oxides at the root surface[10] (Fig. 2a).

Fe is a prominent feature of many permafrost systems where cold, wet conditions produce peat soils with abundant redox interfaces. Fe that is dissolved from deep mineral soils under reducing conditions migrates to these redox interfaces, which are typically present in shallow soils or where groundwater discharges into ponds and streams[11], and accumulates as Fe (oxyhydr)oxides or organic-bound Fe[12] (Fig. 3). These oxidized Fe phases bind organic compounds and provide at least transient stabilization against microbial decomposition[13]. Transitions between oxidizing and reducing conditions with fluctuating water tables promote Fe-mediated decomposition of organic matter[7] and the formation and dissolution of short-range ordered Fe (oxyhydr) oxides that bind OC[4,14].

A wide variety of microbial metabolic processes tightly link Fe redox transformations to C cycling[15], with hotspots for microbial Fe reduction and oxidation found in permafrost regions[16]. Fe(III)-reducing microorganisms couple the reduction of Fe(III) (oxyhydr)oxides to the oxidation of OC, providing a direct mechanism of CO_2 production under anoxic conditions, as is widely observed in Arctic wetlands (for example, ref. 17). This microbial Fe(III) reduction is more energetically favourable than methanogenesis and can act to suppress CH_4 production[18], in turn impacting CO_2:CH_4 ratios and the global warming potential of emissions, given that CH_4 is a more potent GHG. Fe reduction can potentially also facilitate methanogenesis under substrate-rich conditions by increasing the pH to levels favourable for methanogens[19].

Reduced Fe(II), the product of microbial Fe(III) reduction, is recycled by rapid reaction with oxygen under oxic conditions at circumneutral pH. However, under micro-oxic or acidic conditions, microorganisms can successfully compete with abiotic oxidation. Microorganisms that oxidize Fe(II) in oxygen-limited near-neutral environments (neutrophilic micro-aerophilic Fe(II) oxidizers), which thrive at low micromolar concentrations of oxygen and form distinctive stalk or sheath-like Fe mineral structures, have been observed across several permafrost systems both within the active layer[17,20] and as mats in streams[21], thaw ponds[22] and rivers[11]. Under completely anoxic conditions, Fe can also be oxidized by anaerobic phototrophic or nitrate-dependent Fe-oxidizing bacteria[3], although their role in microbial Fe cycling in permafrost regions is still elusive.

Fe–OC interactions from soils to rivers

The extent to which microorganisms can respire Fe and C in permafrost systems is largely dictated by Fe and C composition and physical accessibility. Fe–OC interactions in permafrost-affected soils and sediments are either within soil aggregates, with particulate OC cemented by Fe (oxyhydr)oxides, or in the form of organic-bound Fe complexes or OC bound to short-range ordered Fe(III) (oxyhydr)oxides (for example, refs. 23,24). Across Arctic landscapes, a series of state factors—such as topography, ground ice content, permafrost extent, parent material and thaw history—constrain the biogeochemical effect of thaw[25]. Differences in soil biogeochemistry generate contrasting soil acidity and hence variable affinity between Fe and OC. More soluble Fe at low pH favours the formation of Fe–OC complexes, whereas the precipitation of Fe at high pH favours OC coprecipitation or sorption onto Fe oxides (for example, ref. 23). Organic-bound Fe complexes and short-range ordered Fe(III) (oxyhydr)oxides appear to be the Fe sources that are readily available for Fe(III)-reducing bacteria under anoxic conditions, such that thaw is typically associated with a sharp decrease in OC binding by Fe(III) (oxyhydr)oxides and a sharp increase in dissolved Fe(II) and OC[20,26]. The organic matter released into the dissolved pool during thaw transitions has been observed to be mostly small, aliphatic molecules that may be readily bioavailable[20], although the extent to which increased substrate availability leads to increased C emissions seems to be highly dependent on pH and the geochemistry of individual systems[27]. Once thaw occurs, these newly formed wetlands continue to experience dynamic and seasonal Fe cycling, where Fe–OC assemblages can reform during dry summer months only to be dissolved again in the wet autumn and spring[4]. The formation and dissociation of these Fe–OC assemblages with redox fluctuations can be detected with radiogenic strontium isotopes (Table 1). Learning from past Pleistocene deposits exposed to thaw during the Holocene, the pool of Fe oxides may change in crystallinity upon thaw from more crystalline Fe oxides to short-range ordered[28] phases with a larger surface area to interact with OC[29]. A comprehensive understanding of the stability of OC-associated mineral phases under thaw conditions requires detailed characterization of Fe-bearing mineral phases, especially those relevant to the cycling of Fe through redox transformations or

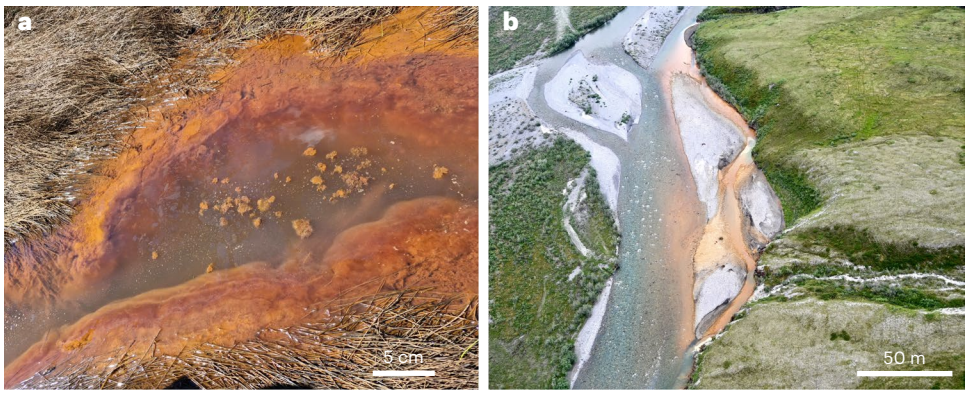

Fig. 3 | Fe precipitates formed in Arctic and sub-Arctic surface waters. a, Photograph of Eight Mile Lake, Alaska from June 2024 showing Fe oxides—resulting from Fe dissolution in a deep mineral soil layer—migrating to a redox interface in the surface, leading to OC coprecipitation or sorption. **b**, Photograph of the Marsh Fork of the Canning River, Alaska, taken by plane, showing Fe oxide precipitation due to a pH change from acidic drainage to carbonate-rich river. Credit: **a**, P. Roux.

sulfide oxidation and to OC stabilization or mobilization (for example, refs. 13,24) (Table 1).

A portion of the Fe–OC assemblages formed in Arctic soils are transferred to aquatic bodies (lakes, rivers and wetlands) as larger particles of Fe–OC coprecipitates and smaller colloidal-size Fe–OC complexes[14]. If large volumes of permafrost material are displaced by physical disturbances such as thaw slumps, Fe–OC assemblages can be preserved in the newly formed deposits[30]. In aquatic bodies, this Fe–OC has two principal fates: (1) transfer along the hydrological continuum and burial in flood plain and estuarine sediments; and/or (2) alteration and Fe–OC breakdown during transport[31]. Whereas burial results in minimal breakdown of OC and minimal transfer of Fe to the Arctic Ocean, alteration results in CO_2 release to the atmosphere and potential transfer of newly formed Fe–OC to the Arctic Ocean, bypassing flocculation in the estuary. To establish the source, processing and fate of Fe–OC in aquatic bodies, various methodologies are used that measure the concentration, size, morphology, mineralogy, oxidation state and isotope composition of Fe (Table 1).

The volume and form of Fe–OC transferred to aquatic bodies is governed by factors including seasonality, permafrost extent, geology, topography and event-scale hydrology. During spring and summer rain events, Fe–OC derived from the litter layer and surface soils is transferred as larger particles to higher-order river systems[32] and may eventually be deposited in riverbed, flood plain or estuarine sediments[33]. This is when Fe–OC can be transferred from permafrost ground to estuarine sediments with a lesser contribution to in-stream GHG release or Fe supply for primary production in the Arctic Ocean. In contrast, during summer and autumn baseflow periods, there is a longer water residence time in soils, allowing for multiple redox cycles, and the Fe–OC interactions in aquatic bodies (Fig. 2b) drive OC breakdown and GHG release from soils[34]. Once in the aquatic body, light and microorganisms (for example, ref. 31) further break down soil-derived Fe–OC to form new Fe–OC (~1 nm in size), contributing to the pool of dissolved inorganic C and the release of GHGs from aquatic bodies in the Arctic[35]. Overall, the relative proportions of soil-derived (larger particles) and in-stream-derived (smaller particles) Fe–OC modulate how much Fe is transferred across estuaries and becomes available for primary production and GHG drawdown in the Arctic Ocean[36].

Arctic rusting

Arctic rusting linked to permafrost thaw has been documented only in the past decade[37] and is increasing in breadth and scale[38]. Permafrost degradation exposes previously frozen soils and sediments to weathering, releasing Fe into porewaters where it can be flushed into oxygenated streams and precipitate as Fe (oxyhydr)oxides. Notably, the oxidation of newly thawed Fe sulfides produces high concentrations of acid, sulfate and dissolved Fe (that is, acid rock drainage). The increasing prevalence of seasonal rusting is altering the water quality of Arctic watershed. Elevated stream Fe concentrations in Arctic and sub-Arctic watersheds[39], combined with its redox sensitivity and the optical detectability of Fe(III)[38], make Fe a useful indicator of landscape-scale permafrost active-layer dynamics.

Although Fe is not inherently toxic at low concentrations, recent levels reported in the Arctic are of concern, as Fe frequently co-occurs with other metal(loid)s that can be toxic or carcinogenic even at trace levels. Permafrost thaw releases Fe along with other redox-sensitive elements, including arsenic (As), uranium (U) and mercury (Hg)[40–42]. Fe may act as both a sink and a vector for them, as well as for C, within watersheds[15,22]. Seasonal Arctic rusting influences water quality, vegetation health and the C cycle, yet its overall impact remains poorly understood.

Many Arctic regions have experienced baseline acid rock drainage for centuries[43], indicating that rusting Arctic rivers are not a wholly new phenomenon. However, the duration, intensity and spatial extent of such events have increased with the thawing of near-surface permafrost. Visually, Arctic rusting manifests as streams running bright orange or red, driven by permafrost active-layer dynamics and pH changes when acidic drainage enters carbonate-rich rivers (Fig. 3). These events are most observed during spring snowmelt, late summer and autumn/early winter, with the latter representing a critical yet understudied period when the active layer reaches its maximum annual depth[26]. Arctic rusting events can exhibit distinct lowland or upland signatures, reflecting differences in source materials and the presence of Fe ore[38,44].

Geophysical techniques such as electrical resistivity tomography and ground-penetrating radar are sensitive to the presence of frozen and unfrozen water within soil systems and can help to identify heterogeneous soil distributions that may contribute to Fe release[44]. The resulting Fe(III) formation can be detected across multiple spatial scales through optical remote sensing of Arctic landscapes. Optical water properties obtained from unmanned aerial vehicles and satellite imagery are integrated with in situ measurements of dissolved and particulate concentrations. Pixel-based Fe oxide index values can be used to estimate Fe concentrations; however, discrepancies may occur between satellite-derived data and the actual chemical composition of soils and river waters, particularly when the signal is confounded by dissolved OC and suspended sediments. Integrating microscale analytical methods with geophysical and remote sensing approaches, alongside catchment-scale mixing models, is recommended to comprehensively assess the extent of Arctic rusting and the downstream ecological implications of Fe.

https://doi.org/10.1038/s41561-026-02015-z

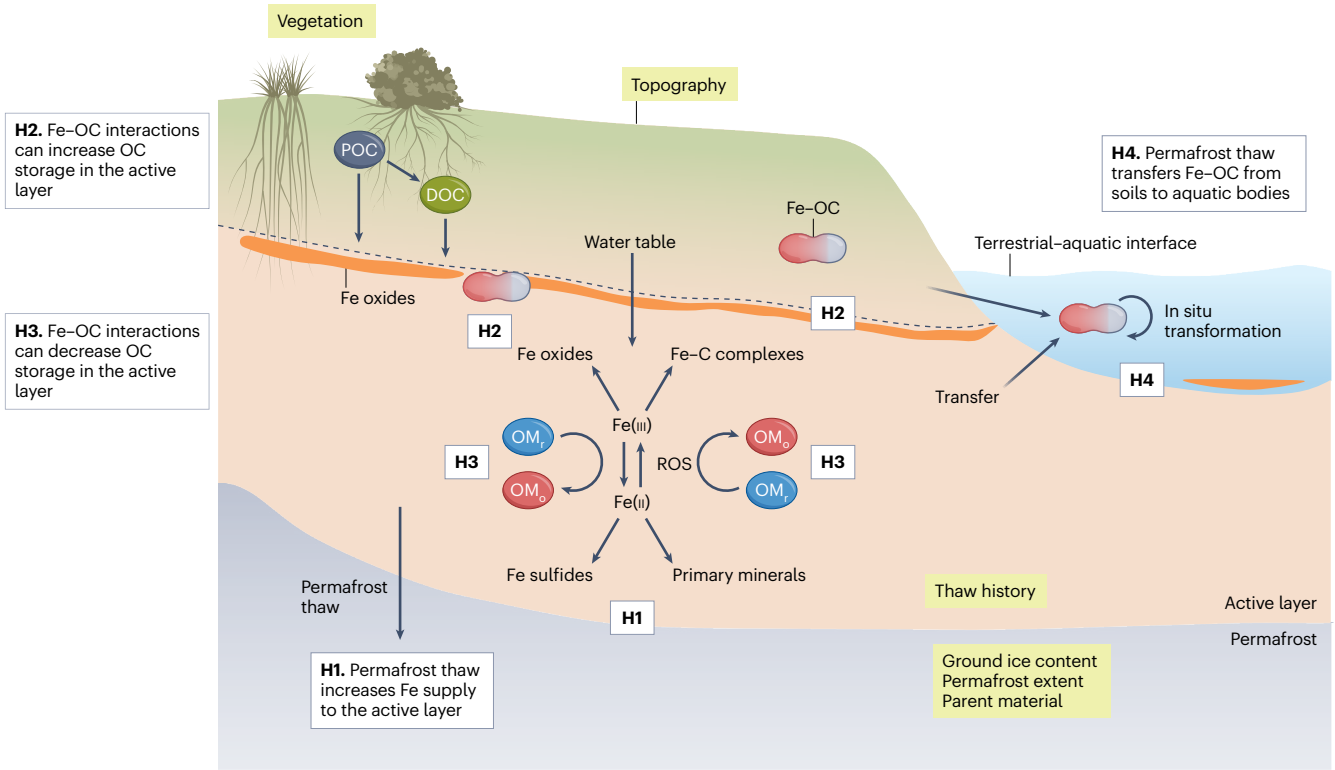

Fig. 4 | Conceptual framework of Fe–OC responses to permafrost thaw. Four testable hypotheses (H1–H4) linked to Fe cycling processes that may drive Fe–OC interactions, thereby modulating permafrost OC release or storage along the soil–river continuum. The shown geochemical reactions are both abiotic and microbially mediated. The state factors[4] to be considered are in light green boxes. DOC, dissolved OCn; OM_o, oxidized organic species, including CO_2; OM_r, reduced organic species, including CH_4; POC, particulate OC; ROS, reactive oxygen species.

Testable hypotheses on Fe–OC fate with permafrost thaw

The net effects of Fe–OC interactions on the Arctic C budget and changes with ongoing warming and permafrost thaw are uncertain. Fe redox cycling can promote organic matter decomposition and CO_2 release to the atmosphere through the biotic and abiotic processes described above. However, Fe (oxyhydr)oxides can sorb or co-precipitate with organic matter to limit decomposition and increase C storage. Permafrost thaw will alter the location, duration and frequency of soil saturation throughout the Arctic. These changes in hydrologic regime will affect the occurrence of oxic or anoxic conditions that promote Fe cycling and Fe–OC interactions, as well as the transport of Fe and C through watersheds. Here we present a conceptual framework describing the integration of these processes across the landscape (Fig. 4). We put forward four testable hypotheses (H1 to H4) to advance understanding of the coupled environmental controls on pore-scale reactions central to global Fe–C cycling.

H1: Permafrost thaw increases Fe supply to the active layer

Permafrost thaw introduces previously frozen minerals into the active layer, where they start to weather. We hypothesize that, depending on state factors such as parent material lithology, continued permafrost thaw will increase concentrations of actively cycling Fe in the active layer by enhancing the oxidative dissolution of Fe sulfides and generating Fe (oxyhydr)oxides and organic-bound Fe that accumulate in soils or are transferred into stream networks. Fe sulfides will persist in deep mineral soils that remain saturated, but will dissolve when exposed to air as water tables lower, or to oxygenated, flowing waters in streams. Fe (oxyhydr)oxides will accumulate near redox interfaces within soil profiles, in pond sediments and along stream banks.

H2: Fe–OC interactions can increase OC storage in the active layer

Given higher reactive Fe concentrations, Fe–OC interactions are hypothesized to increase with permafrost thaw. Increased formation of secondary Fe (oxyhydr)oxides within soils will enhance C storage by providing fresh minerals that bind OC and protect it from microbial respiration. These interactions may assist with stabilizing smaller organic molecules produced through the microbial decomposition of particulate organic matter. That is, enhanced primary productivity and microbial degradation of particulate organic matter with warming will increase the production of small molecules that then bind to minerals newly available through deepening thaw into mineral soils. The formation of new mineral-associated organic matter may be accelerated in soils where drainage facilitates both aerobic decomposition and Fe (oxyhydr)oxide formation.

H3: Fe–OC interactions can decrease OC storage in the active layer

The formation of Fe (oxyhydr)oxides will also promote organic matter decomposition in saturated, anoxic soils by providing an abundant terminal electron acceptor. We hypothesize that increases in the anaerobic respiration of ferric Fe will produce CO_2 and potentially impair methanogenesis due to both the abundance of the more energetically favourable Fe substrate and acidification resulting from sulfide and Fe oxidation. Water table fluctuations throughout the thaw season will drive continued Fe cycling and Fe–OC interactions. For example, dissolved Fe(II) produced through the reductive dissolution of Fe (oxyhydr)oxides in saturated soils will reoxidize as water tables drop throughout the thaw season and air is introduced into pore spaces. The reoxidation of Fe(II) to Fe(III) generates reactive oxygen species that contribute to organic matter degradation and CO_2 release. Model representations of CO^- and CH_4 release that do not account

for these dynamics may fail to adequately capture the net C balance of Arctic ecosystems.

H4: Permafrost thaw transfers Fe–OC from soils to aquatic bodies

We hypothesize that permafrost thaw will also increase Fe mobilization through watersheds due to deepening flow paths through mineral soils and physical erosion that transfer dissolved and particulate Fe from soils into stream networks. Dissolved Fe is readily oxidized to form Fe (oxyhydr)oxides where the pH is non-acidic, leading to the prevalent rusting observed in Arctic streams. Particulate Fe may serve as a vector for the transport of soil OC, whereas oxides that precipitate in the stream will probably bind stream-derived OC. This OC is expected to be protected from respiration as long as the Fe persists in oxygenated waters, but may be susceptible to decomposition if Fe oxides settle into anoxic sediments and are dissolved. It is unclear whether enhanced Fe mobilization into streams increases Fe loading into oceans. As described above, particulate Fe (and associated OC) can be stored in stream bed sediments and is particularly susceptible to sequestration in estuaries where sediments flocculate. The transfer of Fe and OC to the ocean may be higher in areas where Fe remains dissolved due to lower pH.

Future directions

We outline future research directions aimed at integrating challenges across scales and reducing key uncertainties in quantifying the net effects of Fe–OC interactions on the Arctic C budget using scale-adapted approaches (Table 1).

(1) To better predict the supply of Fe to the active layer (H1), state factors[25]—such as topography, ground ice content, permafrost extent, parent material and thaw history—are essential. This is why a multi-site approach is needed. A key parameter often neglected is ground porosity largely controlling water flow paths and loci for microbial activity. The use of geophysical techniques can help to assess ground porosity and track seasonal changes in volumetric water content.

(2) A better quantification of how Fe–OC interactions increase (H2) or decrease (H3) OC storage in the active layer also requires consideration of how state factors such as parent material and vegetation affect pH, Fe supply and weathering pathways, and C input and composition (Table 1). This is particularly needed to refine understanding of the role of microorganisms in the formation, stability and transformation of Fe–OC interactions in permafrost regions. Given that Fe–OC assemblages act as traps for nutrients such as phosphorus[12,45,46], improving our understanding of the fate of these interactions upon permafrost thaw is relevant for the cycling of other nutrients. Finally, the evolution of Fe–OC interactions upon permafrost thaw also applies to subsea permafrost C[47], a context where the coupled environmental controls on pore-scale reactions should also be investigated in more detail.

(3) A better prediction of the future trajectory of the Arctic incorporating the effects of Fe on C cycling (H2 and H3) requires the inclusion of redox processes in Earth system models (ESMs). ESMs typically represent microbial decomposition as binary between aerobic metabolism in drained soils and methanogenic pathways in inundated soils[48]. Recent advances in coupling ESMs with reactive transport models that represent redox processes will enable more nuanced simulation of soil biogeochemistry[49], including Fe metabolic pathways (Table 1).

(4) To better assess the transfers of Fe–OC interactions from soils to the hydrosphere upon permafrost thaw (H4), it should be considered that older OC is being mobilized from permafrost soils during spring[50], which is evidence for pre-snowmelt connectivity and the transfer of OC and Fe[51]. However, what proportion of old OC is bound to Fe and whether Fe controls the fate of older OC released from permafrost is unclear. In addition, elevated Fe concentrations in aquatic bodies derive from Fe sulfide oxidation leading to Arctic rusting[38], but whether the newly released Fe binds to OC and to what extent this Fe will modulate the OC fate remains uncertain. Finally, we have yet to gain enough data to truly quantify the relative contribution of microbial Fe–OC transformation to C emissions from soils to rivers; data that are necessary to upscale from these microorganism- and mineral-scale reactions to the landscape.

(5) Ample opportunity exists to explore interactions between Fe and OC in Arctic systems, particularly for estimating the magnitude of these changes and their effects on C storage and release. These studies should focus both on the micrometre-scale microbial and geochemical processes that underlie Fe–OC interactions and the pedon- and landscape-scale processes that transport Fe and OC through watersheds and affect their susceptibility to transformation. In addition, future studies should explicitly consider the role of seasonal transitions in regulating Fe and OC release from soils[26,34,51], as well as the effects of increasing precipitation on permafrost thaw and hydrological flow paths[52], which may cause Arctic and sub-Arctic regions to become wetter or drier depending on state factors such as ice content and topography, thereby modulating where, when and how much Fe and OC are transferred along the soil–river continuum.

References

1. Strauss, J. et al. in *Encyclopedia of Quaternary Science* 3rd edn, Vol. 5 (ed. Elias, S.) 399–410 (Elsevier, 2025).
2. Liljedahl, A. K. et al. Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nat. Geosci.* **9**, 312–318 (2016).
3. Herndon, E., Kinsman-Costello, L. & Godsey, S. in *Biogeochemical Cycles: Ecological Drivers and Environmental Impact* (eds Dontsova, K. et al.) 245–265 (American Geophysical Union, 2020).
4. Patzner, M. S. et al. Seasonal fluctuations in iron cycling in thawing permafrost peatlands. *Environ. Sci. Technol.* **56**, 4620–4631 (2022).
5. Lehmann, J. & Kleber, M. The contentious nature of soil organic matter. *Nature* **528**, 60–68 (2015).
6. Kokelj, S. V. & Jorgenson, M. T. Advances in thermokarst research. *Permafr. Periglac. Process.* **24**, 108–119 (2013).
7. Trusiak, A., Treibergs, L. A., Kling, G. W. & Cory, R. M. The role of iron and reactive oxygen species in the production of CO_2 in arctic soil waters. *Geochim. Cosmochim. Acta* **224**, 80–95 (2018).
8. Lipson, D. A., Jha, M., Raab, T. K. & Oechel, W. C. Reduction of iron (III) and humic substances plays a major role in anaerobic respiration in an Arctic peat soil. *J. Geophys. Res. Biogeosci.* **115**, G00I06 (2010).
9. Roy Chowdhury, T. et al. Stoichiometry and temperature sensitivity of methanogenesis and CO_2 production from saturated polygonal tundra in Barrow, Alaska. *Glob. Change Biol.* **21**, 722–737 (2015).
10. Rooney, E. C. et al. Decoupling of redox processes from soil saturation in Arctic tundra. *Commun. Earth Environ.* **5**, 746 (2024).
11. Emerson, D., Scott, J. J., Benes, J. & Bowden, W. B. Microbial iron oxidation in the Arctic tundra and its implications for biogeochemical cycling. *Appl. Environ. Microbiol.* **81**, 8066–8075 (2015).
12. Herndon, E. M. et al. Iron (oxyhydr)oxides serve as phosphate traps in tundra and boreal peat soils. *J. Geophys. Res. Biogeosci.* **124**, 227–246 (2019).
13. Patzner, M. S. et al. Iron mineral dissolution releases iron and associated organic carbon during permafrost thaw. *Nat. Commun.* **11**, 6329 (2020).

14. Pokrovsky, O. S. & Schott, J. Iron colloids/organic matter associated transport of major and trace elements in small boreal rivers and their estuaries (NW Russia). *Chem. Geol.* **190**, 141–179 (2002).
15. Kappler, A. et al. An evolving view on biogeochemical cycling of iron. *Nat. Rev. Microbiol.* **19**, 360–374 (2021).
16. Epihov, D. & Bryce, C. Contrasting microbial communities drive iron cycling across global biomes. Preprint at *Research Square* https://doi.org/10.21203/rs.3.rs-4248419/v1 (2024).
17. Michaud, A. B., Massé, R. O. & Emerson, D. Microbial iron cycling is prevalent in water-logged Alaskan Arctic tundra habitats, but sensitive to disturbance. *FEMS Microbiol. Ecol.* **99**, fiad013 (2023).
18. Voggenreiter, E. et al. Suppression of methanogenesis by microbial reduction of iron–organic carbon associations in fully thawed permafrost soil. *J. Geophys. Res. Biogeosci.* **130**, e2024JG008650 (2025).
19. Sulman, B. N. et al. Simulated hydrological dynamics and coupled iron redox cycling impact methane production in an Arctic soil. *J. Geophys. Res. Biogeosci.* **127**, e2021JG006662 (2022).
20. Patzner, M. et al. Microbial iron cycling during palsa hillslope collapse promotes greenhouse gas emissions before complete permafrost thaw. *Commun. Earth Environ.* **3**, 76 (2022).
21. ThomasArrigo, L. K. et al. Mineral characterization and composition of Fe-rich flocs from wetlands of Iceland: Implications for Fe, C and trace element export. *Sci. Total Environ.* **816**, 151567 (2022).
22. Chauhan, A. et al. Interactions between iron and carbon in permafrost thaw ponds. *Sci. Total Environ.* **946**, 174321 (2024).
23. Monhonval, A. et al. Mineral organic carbon interactions in dry versus wet tundra soils. *Geoderma* **436**, 116552 (2023).
24. Thomas, M. et al. A third of organic carbon is mineral bound in permafrost sediments exposed by the world's largest thaw slump, Batagay, Siberia. *Permafr. Periglac. Process.* **35**, 278–293 (2024).
25. Tank, S. E. et al. Landscape matters: predicting the biogeochemical effects of permafrost thaw on aquatic networks with a state factor approach. *Permafr. Periglac. Process.* **31**, 358–370 (2020).
26. Villani, C. H. et al. Lengthening of biogeochemical processes during winter in degraded permafrost soils. *Geochem. Perspect. Lett.* **34**, 36–42 (2025).
27. Philben, M. et al. Anaerobic respiration pathways and response to increased substrate availability of Arctic wetland soils. *Environ. Sci. Process. Impacts* **22**, 2070–2083 (2020).
28. Monhonval, A. et al. Thermokarst processes increase the supply of stabilizing surfaces and elements (Fe, Mn, Al, and Ca) for mineral–organic carbon interactions. *Permafr. Periglac. Process.* **33**, 452–469 (2022).
29. Voggenreiter, E. et al. Emerging investigator series: preferential adsorption and coprecipitation of permafrost organic matter with poorly crystalline iron minerals. *Environ. Sci. Process. Impacts* **26**, 1322–1335 (2024).
30. Thomas, M. et al. Evidence for preservation of organic carbon interacting with iron in material displaced from retrogressive thaw slumps: case study in Peel Plateau, western Canadian Arctic. *Geoderma* **433**, 116443 (2023).
31. Bowen, J. C., Ward, C. P., Kling, G. W. & Cory, R. M. Arctic amplification of global warming strengthened by sunlight oxidation of permafrost carbon to CO_2. *Geophys. Res. Lett.* **47**, e2020GL087085 (2020).
32. Hirst, C. et al. Iron isotopes reveal seasonal variations in the mechanisms for iron-bearing particle and colloid formation in the Lena River catchment, NE Siberia. *Geochim. Cosmochim. Acta* **363**, 77–93 (2023).
33. Conrad, S. et al. Distribution of Fe isotopes in particles and colloids in the salinity gradient along the Lena River plume, Laptev Sea. *Biogeosciences* **16**, 1305–1319 (2019).
34. Hirst, C. et al. Seasonal changes in hydrology and permafrost degradation control mineral element-bound DOC transport from permafrost soils to streams. *Global Biogeochem. Cycles* **36**, e2021GB007105 (2022).
35. Song, C. et al. Inland water greenhouse gas emissions offset the terrestrial carbon sink in the northern cryosphere. *Sci. Adv.* **10**, eadp0024 (2024).
36. Vonk, J. E. et al. The land–ocean Arctic carbon cycle. *Nat. Rev. Earth Environ.* **6**, 86–105 (2025).
37. Barker, A. J. et al. Late season mobilization of trace metals in two small Alaskan arctic watersheds as a proxy for landscape scale permafrost active layer dynamics. *Chem. Geol.* **381**, 180–193 (2014).
38. O'Donnell, J. A. et al. Metal mobilization from thawing permafrost to aquatic ecosystems is driving rusting of Arctic streams. *Commun. Earth Environ.* **5**, 268 (2024).
39. Stimmler, P. et al. Pan-Arctic soil element bioavailability estimations. *Earth Syst. Sci. Data* **15**, 1059–1075 (2023).
40. Skierszkan, E. K. et al. Arsenic mobilization from thawing permafrost. *ACS Earth Space Chem.* **8**, 745–759 (2024).
41. Skierszkan, E. K., Schoepfer, V. A., Fellwock, M. & Lindsay, M. B. J. Uranium speciation and mobilization in thawing permafrost. *Environ. Sci. Technol.* **58**, 17058–17069 (2024).
42. Smith, M. I. et al. Mercury stocks in discontinuous permafrost and their mobilization by river migration in the Yukon River Basin. *Environ. Res. Lett.* **19**, 084041 (2024).
43. de Koven Leffingwell, E. *The Canning River Region, Northern Alaska*. United States Geological Survey Professional Paper 109 (US Geological Survey, 1919); https://doi.org/10.3133/pp109.
44. Barker, A. J. et al. Iron oxidation–reduction processes in warming permafrost soils and surface waters expose a seasonally rusting Arctic watershed. *ACS Earth Space Chem.* **7**, 1479–1495 (2023).
45. Berens, M. J. et al. Phosphorus interactions with iron in undisturbed and disturbed Arctic tundra ecosystems. *Environ. Sci. Technol.* **58**, 11400–11410 (2024).
46. Barczok, M. et al. Iron transformation mediates phosphate retention across a permafrost thaw gradient. *Commun. Earth Environ.* **5**, 635 (2024).
47. Miesner, F. et al. Subsea permafrost organic carbon stocks are large and of dominantly low reactivity. *Sci. Rep.* **13**, 9425 (2023).
48. Melton, J. R. et al. Present state of global wetland extent and wetland methane modelling: conclusions from a model inter-comparison project (WETCHIMP). *Biogeosciences* **10**, 753–788 (2013).
49. Sulman, B. N. & Herndon, E. M. Modeling interactive effects of manganese bioavailability, nitrogen deposition, and warming on soil carbon storage. *J. Geophys. Res. Biogeosci.* **129**, e2023JG007830 (2024).
50. Schwab, M. S. et al. An abrupt aging of dissolved organic carbon in large Arctic rivers. *Geophys. Res. Lett.* **47**, e2020GL088823 (2020).
51. Hirst, C. et al. Evidence for late winter biogeochemical connectivity in permafrost soils. *Commun. Earth Environ.* **4**, 85 (2023).
52. Jorgenson, K. L., Douglas, T. A., Jorgenson, M. T., Pastick, N. J. & Harms, T. K. Permafrost and rain influence summer hydrologic flowpaths in boreal catchments. *Water Resour. Res.* **61**, e2024WR039024 (2025).
53. Baker, C. C., Barker, A. J., Douglas, T. A., Doherty, S. J. & Barbato, R. A. Seasonal variation in near-surface seasonally thawed active layer and permafrost soil microbial communities. *Environ. Res. Lett.* **18**, 055001 (2023).

54. Herndon, E. et al. Influence of iron redox cycling on organo-mineral associations in Arctic tundra soil. *Geochim. Cosmochim. Acta* **207**, 210–231 (2017).
55. Hirst, C. et al. Characterisation of Fe-bearing particles and colloids in the Lena River basin, NE Russia. *Geochim. Cosmochim. Acta* **213**, 553–573 (2017).
56. Mueller, C. W. et al. Microscale soil structures foster organic matter stabilization in permafrost soils. *Geoderma* **293**, 44–53 (2017).
57. Gentsch, N. et al. Properties and bioavailability of particulate and mineral-associated organic matter in Arctic permafrost soils, Lower Kolyma Region, Russia. *Eur. J. Soil Sci.* **66**, 722–734 (2015).
58. Barczok, M. et al. Influence of contrasting redox conditions on iron (oxyhydr)oxide transformation and associated phosphate sorption. *Biogeochemistry* **166**, 87–107 (2023).
59. Joss, H. et al. Cryoturbation impacts iron–organic carbon associations along a permafrost soil chronosequence in northern Alaska. *Geoderma* **413**, 115738 (2022).
60. Wortberg, K., Conrad, S., Andersson, P. S. & Ingri, J. Strontium isotopes—a tracer for river suspended iron aggregates. *Appl. Geochem.* **79**, 85–90 (2017).
61. Monhonval, A., Hirst, C., Strauss, J., Schuur, E. A. G. & Opfergelt, S. Strontium isotopes trace the dissolution and precipitation of mineral organic carbon interactions in thawing permafrost. *Geoderma* **433**, 116456 (2023).
62. Andresen, C. G. et al. Soil moisture and hydrology projections of the permafrost region—a model intercomparison. *Cryosphere* **14**, 445–459 (2020).
63. Schneider von Deimling, T. et al. Consequences of permafrost degradation for Arctic infrastructure—bridging the model gap between regional and engineering scales. *Cryosphere* **15**, 2451–2471 (2021).
64. Opfergelt, S. The next generation of climate model should account for the evolution of mineral–organic interactions with permafrost thaw. *Environ. Res. Lett.* **15**, 091003 (2020).
65. Du Bois d'Aische, E. et al. Permafrost thaw drives iron and organic carbon release into soil pore water during palsa to degraded palsa transition. *Permafr. Periglac. Process.* **37**, 107–123 (2025).
66. Vasyukova, E. V. et al. Trace elements in organic- and iron-rich surficial fluids of the boreal zone: assessing colloidal forms via dialysis and ultrafiltration. *Geochim. Cosmochim. Acta* **74**, 449–468 (2010).
67. Krickov, I. V. et al. Colloidal transport of carbon and metals by western Siberian rivers during different seasons across a permafrost gradient. *Geochim. Cosmochim. Acta* **265**, 221–241 (2019).
68. Ilina, S. M. et al. Extreme iron isotope fractionation between colloids and particles of boreal and temperate organic-rich waters. *Geochim. Cosmochim. Acta* **101**, 96–111 (2013).
69. Oleinikova, O. V. et al. Dissolved organic matter degradation by sunlight coagulates organo-mineral colloids and produces low-molecular weight fraction of metals in boreal humic waters. *Geochim. Cosmochim. Acta* **211**, 97–114 (2017).
70. Hirst, C. et al. Iron isotopes reveal the sources of Fe-bearing particles and colloids in the Lena River basin. *Geochim. Cosmochim. Acta* **269**, 678–692 (2020).
71. Herzog, S. D., Persson, P., Kvashnina, K. & Kritzberg, E. S. Organic iron complexes enhance iron transport capacity along estuarine salinity gradients of Baltic estuaries. *Biogeosciences* **17**, 331–344 (2020).
72. Folhas, D., Couture, R.-M., Laurion, I., Vieira, G. & Canário, J. Natural organic matter dynamics in permafrost peatlands: critical overview of recent findings and characterization tools. *Trends Anal. Chem.* **184**, 118153 (2025).
73. Douglas, T. A., Turetsky, M. R. & Koven, C. D. Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. *npj Clim. Atmos. Sci.* **3**, 28 (2020).
74. Raudina, T. V. et al. Contrasting soil temperature regimes in peatlands of the discontinuous permafrost zone (western Siberia). *Geoderma* **457**, 117294 (2025).
75. Tikhomirov, A. B., Lesins, G. & Drummond, J. R. Drone measurements of surface-based winter temperature inversions in the High Arctic at Eureka. *Atmos. Meas. Tech.* **14**, 7123–7145 (2021).
76. Alphonse, A. B., Osuch, M., Wawrzyniak, T. & Hanselmann, N. Spatio-temporal variability of surface temperatures in High Arctic periglacial environment using UAV thermal imagery and in-situ measurements. *GISci. Remote Sens.* **61**, 2435851 (2024).
77. Martinez, J.-M., Espinoza-Villar, R., Armijos, E. & Silva Moreira, L. The optical properties of river and floodplain waters in the Amazon River Basin: implications for satellite-based measurements of suspended particulate matter. *J. Geophys. Res. Earth Surf.* **120**, 1274–1287 (2015).
78. Liu, M. et al. Global riverine land-to-ocean carbon export constrained by observations and multi-model assessment. *Nat. Geosci.* **17**, 896–904 (2024).

Acknowledgements

We are grateful for the opportunity to have discussed these issues within our respective research groups. S.O. has been supported by funding from the European Research Council under the European Union's Horizon 2020 research and innovation programme (European Research Council Starting Grant WeThaw; agreement 714617), Fonds National de la Recherche Scientifique (FC69480 and CDR MOIST) and Belgian Science Policy (BELSPO IMPULS; RT/23/LIFTHAW). E.M.H. was supported by the Next-Generation Ecosystem Experiments in the Arctic project, funded by the Biological and Environmental Research programme in the Department of Energy's Office of Science. Funding for A.J.B. was provided by the Assistant Secretary of the Army for Acquisition, Logistics, and Technology's Basic and Applied Research Framework under specific projects The Rusting of the Arctic and Soil Moisture Controls on the Thermal Regime of Arctic Soils. This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (https://www.energy.gov/doe-public-access-plan).

Author contributions

S.O. managed co-author contributions. S.O. prepared the figures with direct contributions from A.J.B., E.M.H. and C.H. and feedback from all authors. All authors wrote the manuscript, participated in discussions and edited and revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence should be addressed to S. Opfergelt.

Peer review information *Nature Geoscience* thanks Jon Chorover and Donald Sparks for their contribution to the peer review of this work.

Primary Handling Editor: Camilla Brunello, in collaboration with the *Nature Geoscience* team.