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Inhibition of Arctic Soil Dissolved Organic Carbon Export by the Retention Capacity of Thawing Permafrost

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Key Points:

- Significant amount of soil organic carbon can be released from mineral permafrost as dissolved organic carbon (DOC), comparable to carbon loss through microbial decomposition
- As permafrost thaws, retention of DOC from upper soils during vertical transport could impact the overall release of DOC from Arctic soils
- There is an expected increase in the lability of soil DOC as deeper permafrost tends to retain aromatic compounds from upper soils

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Permafrost thawing is mobilizing dissolved organic carbon (DOC) stored in Arctic frozen soils into rivers, but vertical transport mechanisms within soil columns remain unclear, hindering accurate estimation of soil-derived DOC export. Through leaching experiments on active-layer organic soils and underlying mineral permafrost, this study reveals that mineral permafrost exhibits high soil carbon loss as DOC (3.27%–11.42%). However, 11.17%–46.42% of active-layer DOC is retained by mineral permafrost during vertical transport, forming an internal soil carbon sink. The sink selectively retains aromatic compounds, acting as a molecular “filter” that alters DOC composition and bioavailability. This internal retention complicates interpretations of active-layer DOC transport dynamics and alters the chemistry of both thawed permafrost and exported DOC. The findings emphasize the critical role of intra-soil DOC transformations in Arctic carbon cycling.

Plain Language Summary Due to rising temperatures in the Arctic, the permanently frozen ground (permafrost) faces severe thawing threats. As permafrost thaws, the organic carbon (OC) stored within it may be released through different ways, including microbial decomposition into greenhouse gases and transport to fluvial or marine systems in dissolved and particulate forms. However, the mechanisms controlling the transport of dissolved-phase OC (DOC) through soils and its transformations before entering fluvial and marine systems are poorly understood. In this study, we investigate the vertical transport of soil DOC and demonstrate that a portion of upper organic-rich soil DOC can be retained in deeper, mineral-rich soil layers. Additionally, the chemical composition of soil DOC may be modified during vertical transport, influencing the properties of soil OC exported to fluvial and marine systems. Our findings underscore the need for a deeper understanding of DOC mobilization within Arctic soil columns.

1. Introduction

Rapid temperature rise in the Arctic is threatening the stability of frozen ground and is causing severe geomorphic and ecological issues (Biskaborn et al., 2019; Smith et al., 2022; Streletskiy et al., 2023). The thawing of perennially frozen soils (permafrost) exposes substantial amounts of organic carbon (OC) to microbial decomposition, some of which has been frozen for hundreds to tens of thousands of years or more (Miner et al., 2022; Schuur et al., 2015). The carbon pool in the permafrost region, estimated to be twice the amount in the atmospheric carbon pool, could significantly impact global carbon cycling if destabilized and released as greenhouse gases following thaw (Hugelius et al., 2014). This process represents a natural positive feedback known as the permafrost carbon feedback, whose magnitude and timing are critical for understanding ongoing and future climate change (Schuur et al., 2015, 2022).

Dissolved organic carbon (DOC) is easily mobilized by flowing water and is the major form of OC export from river watersheds into the Arctic Ocean (Dittmar & Kattner, 2003; Vonk et al., 2025). The transport of permafrost-derived DOC (DOC_P) in Arctic fluvial systems has been recorded in many studies (Guo et al., 2007; Spencer et al., 2015; Wild et al., 2019). Despite being stored for thousands of years or more, OC in permafrost can be extremely labile, especially the DOC_P (Drake et al., 2015; Mann et al., 2015; Spencer et al., 2015). As temperatures rise, more old and reactive DOC_P could be released into fluvial systems (Mann et al., 2022) because of enhanced hydrological connectivity via groundwater flow paths (Frey & McClelland, 2009; Mohammed et al., 2022), eventually affecting Arctic ecosystem carbon balance and carbon flux estimations.

Theoretically, future DOC_P release from permafrost via both gradual (e.g., active layer thickening) and abrupt (e.g., thermokarst) thaw processes would augment the existing DOC flux derived from current active layer and thermokarst-affected soils, as documented in historical and contemporary observations (Guo et al., 2007; Heffernan et al., 2024; Spencer et al., 2015; Wild et al., 2019). However, this conventional perspective fails to account for the mineral soil dominance beneath organic-rich surface layers in most permafrost systems. Many studies have shown that mineral-associated OC can be effectively stabilized through organo-mineral interactions (Beare et al., 2014; Bianchi et al., 2024; Feng et al., 2013; Lim et al., 2022), with the majority of OC storage occurring in association with fine silt and clay fractions (Han et al., 2016; Martens et al., 2023). Importantly, mineral protection mechanisms have been observed for permafrost-derived OC upon thaw (Gentsch et al., 2018; Liu et al., 2022; Martens et al., 2023). As permafrost thaw intensifies, high-concentration DOC leached from organic-rich upper soils may infiltrate deeper mineral horizons, where organo-mineral interactions are likely to exert significant control. In temperate soil columns, retention of surface-derived DOC in deep mineral soils through sorption has been recognized (Guggenberger & Kaiser, 2003; Kalbitz & Kaiser, 2008; Kalbitz et al., 2005). However, this phenomenon has not been explicitly documented or investigated in permafrost regions. Therefore, we hypothesize that upon thaw, mineral permafrost retains a fraction of upper active layer soil DOC during vertical percolation, thereby altering both the amount of DOC exported from Arctic soils and its chemical composition.

To test this hypothesis, we conducted a series of leaching experiments on organic-rich active-layer soils and mineral-rich permafrost soils from Alaska. In these experiments, leaching rates and flow paths were controlled to simulate vertical percolation of upper soil DOC into deeper mineral permafrost—a process that is difficult to control in situ due to complex hydrological conditions and the impermeability of current frozen permafrost. We quantified DOC loss during downward percolation and analyzed leachate optical properties to study changes in DOC concentration and chemical characteristics during vertical transport. If confirmed, these processes could significantly influence Arctic carbon flux estimates and cycling dynamics.

2. Materials and Methods

2.1. Sample Collection

Two soil cores were collected from two typical permafrost research sites in northern and southern Alaska—near Barrow (BWT) and Denali National Park (EML)—representing different elevations, climatic conditions, and soil properties (Hutchings et al., 2019; Kanevskiy et al., 2017) (Figure S1 and Text S1 in Supporting Information S1). The BWT site is located within the continuous permafrost zone while EML is located within discontinuous permafrost zone (Jorgenson et al., 2008). More details on the two soil cores can be found in Text S1 in Supporting Information S1. After collection, soil cores were transported frozen to the lab for segmentation and then freeze-dried for storage.

Mineral soils in the Arctic permafrost are loosely defined either by total organic carbon (TOC) content (Fouché et al., 2020; Plaza et al., 2019) or soil depth (Connolly et al., 2020; Ward & Cory, 2015). Based on the TOC of permafrost soil profiles in various Arctic regions (Hugelius et al., 2014; Kanevskiy et al., 2011; Strauss et al., 2015), we define mineral permafrost soil in this study as soil deeper than 1 m with TOC $<5\%$. In this study, we selected four organic-rich active-layer soils (BWT 28–37 cm, BWT 55–62 cm, EML 43–48 cm, and EML 60–67 cm) and three mineral permafrost samples (BWT 182–191 cm, EML 141–147 cm, and EML 259–267 cm) for the leaching experiment (Table S1 in Supporting Information S1). All mineral layers extend sufficiently deep to intersect the permafrost horizon. The samples used in the experiment were sifted for large debris over 2 mm.

2.2. Leaching Procedure

The leaching setup was adapted from a previous study (Zhang et al., 2017). Briefly, freeze-dried soil samples were packed into 20 mL glass syringes and leached at constant flow rates using peristaltic pumps (Figure S2 in Supporting Information S1). Glass fiber filters were placed above and below the soil material to evenly distribute the leaching solution and filter the leachates, respectively. The leaching solution flow rates were maintained between 70 and 100 $\mu L\ min^{-1}$—the maximum velocity just below the threshold that would cause solution accumulation above the soil surface. These rates correspond to 12–17 $mm\ hr^{-1}$ in terms of rainfall rate (Text S2 in Supporting Information S1). The setup was maintained at ambient temperature while the input leaching solution was kept at 0°C to simultaneously control microbial activities and simulate field temperature conditions. All glassware was combusted overnight at 550°C prior to use and wrapped in aluminum foil during the experiment to prevent contamination and photochemical impact.

The study comprise two sequential experiments: an artificial rainwater leaching experiment and a percolation experiment (Figure S3 in Supporting Information S1). In the artificial rainwater leaching experiment, we used synthetic rainwater (Text S2 in Supporting Information S1) as the leaching solution to examine DOC release patterns from both soil horizons (Figures S2 and S3 in Supporting Information S1). Leachates from the upper soil horizon were collected in 15 mL aliquots, while mineral permafrost leachates were collected in 8 mL aliquots. Over 3 days for upper soils and 2 days for permafrost, we collected total of 225 mL (15 vials) and 80 mL (10 vials) of leachates, respectively. These volumes correspond to 620 and 220 mm in terms of rainfall depth (Text S2 in Supporting Information S1). During overnight breaks, leaching columns were sealed and stored at 4°C. For upper soil leachates, we reserve 5 mL from each vial for DOC and optical analyses. The remaining solution from all upper soil collections was combined to create mixed leachates for subsequent percolation experiments. The mixed upper soil leachates were percolated through mineral permafrost soils under identical flow conditions as in the rainwater leaching experiment for permafrost samples. We collected permafrost leachates in 8 mL aliquots (10 vials total), mirroring the collection protocol of the mineral permafrost phase in the artificial rainwater experiment. Leaching experiments were conducted in duplicates or triplicates for each sample.

2.3. Bulk TOC Analysis

The homogenized soil samples were fumigated in a desiccator with 12 N HCl overnight to remove inorganic carbon (Harris et al., 2001), and then oven dried at 50°C for 48 hr. The TOC of samples was measured by Flash Elemental Analyzer interfaced with a Delta V Advantage isotope ratio mass spectrometer by Thermo Fisher Scientific. Each sample was measured in duplicates. The relative standard deviation of USGS40 standards was measured to be 0.4% for TOC.

2.4. DOC and UV-Vis Absorption Measurements

5 mL leachate from each collection and the upper soil leachate mixture were diluted to 20 mL with Milli-Q water before DOC and UV-vis absorbance measurements. DOC concentration was measured using high temperature catalytic oxidation method on a Shimadzu TOC-L CPH analyzer (Guo et al., 1994). To remove inorganic carbon, the solution was acidified to pH < 2 before analysis. At least three injections were performed for each sample, with a coefficient of variance less than 2%. After blank subtraction for Milli-Q water, the DOC concentration was multiplied by the dilution ratio to obtain the original DOC concentration of the leachates. The UV-vis absorbance of the leachates was determined on an Agilent Technologies Cary 300 UV-Vis Spectrophotometer in the range of 200–800 nm with 1 nm increments. The results were corrected for Milli-Q water blank and adjusted to the original absorbance value based on the dilution ratio.

Two optical proxies were calculated based on the results. The specific ultraviolet absorbance at 254 nm (SUVA_{254}) was calculated as

$$\mathrm{SUVA}_{254} = \frac{\mathrm{A}_{254}}{\mathrm{DOC} \times r} \tag{1}$$

where A_{254} is the absorbance at 254 nm and r is the cuvette path length (Weishaar et al., 2003).

The absorption coefficient at 350 nm (a_{350}) was calculated as

$$a_{350} = \frac{2.303\, A_{350}}{r} \tag{2}$$

where A_{350} is the absorbance at 350 nm across the path length r in meters (Hernes & Benner, 2003).

2.5. Statistical Analysis

The percentage of leachable OC in total soil OC is calculated as

$$\text{DOC yield} = \frac{\sum_{i=1}^{n} \text{DOC}_i \times V_i}{M \times \text{TOC}} \tag{3}$$

where n represents the number of collections of the leaching experiments. M indicates the mass of soil samples. TOC is the total organic carbon content (%) of the soil samples. The leaching volume V is 15 mL for upper soils and 8 mL for mineral permafrost samples.

The amount of DOC released from unit volume is calculated as

$$\text{DOC release} = \text{DOC yield} \times \text{TOC} \times \rho \tag{4}$$

where ρ is dry bulk density of soil samples.

The amount of OC retention by mineral permafrost of each collection was calculated as

$$\Delta\text{DOC} = \text{DOC}_{\text{P-U-mix}} - (\text{DOC}_{\text{U-mix}} + \text{DOC}_{\text{P-AR}}) \tag{5}$$

where $\text{DOC}_{\text{P-U-mix}}$ represents the concentration of collections from mineral permafrost leached by mixed upper soil leachate. $\text{DOC}_{\text{U-mix}}$ is the concentration of mixed upper soil leachate. $\text{DOC}_{\text{P-AR}}$ indicates DOC leached from permafrost by artificial rainwater.

The percentage of OC retention by mineral permafrost was calculated as

$$\text{OC retention} = \frac{\sum_{i=1}^{n} (\text{DOC}_{\text{P-AR},i} + \text{DOC}_{\text{U-mix},i} - \text{DOC}_{\text{P-U-mix},i})}{\text{DOC}_{\text{U-mix}} \times n} \times 100\% \tag{6}$$

where n represents the number of collections during percolation experiment.

The normalized OC retention by mineral permafrost was calculated as

$$\text{Normalized OC retention} = \frac{\sum_{i=1}^{n} (\text{DOC}_{\text{P-AR},i} + \text{DOC}_{\text{U-mix},i} - \text{DOC}_{\text{P-U-mix},i}) \times V}{M_{\text{D}}} \times \rho \tag{7}$$

where ρ is the dry bulk density of mineral permafrost samples. M indicates the mass of soil samples and V is the volume of each collection (8 mL).

3. Results and Discussion

3.1. Export of DOC From Different Soil Horizons

Our artificial rainwater leaching experiment demonstrates that DOC mobilization is a major part of soil carbon loss. In this experiment, DOC leached from the upper active layer soil is termed as $\text{DOC}_{\text{U-AR}}$, while DOC collected from mineral permafrost is termed as $\text{DOC}_{\text{P-AR}}$ (Figure S3 in Supporting Information S1). Under our experimental conditions, the majority of $\text{DOC}_{\text{U-AR}}$ and $\text{DOC}_{\text{P-AR}}$ should have been collected as DOC concentrations decrease exponentially to nearly 0 mg L^{-1} in later stages (Figure S4 in Supporting Information S1). By dividing the total amount of OC in all leachates by soil OC, we obtain the percentage of carbon loss as leachable DOC from soils and define it as DOC yield (Methods). In the artificial rainwater leaching experiment, DOC yields of both active layer soil and deeper mineral permafrost are substantial, with higher values in the latter (3.27%–11.42%) than the former (0.80%–4.28%) (Figure 1a, Table S1 in Supporting Information S1). DOC yields from upper organic-rich active layers align with findings from other Arctic leaching experiments (Guo et al., 2007; Neff & Hooper, 2002) and are generally lower than those from deeper mineral permafrost (Fouché et al., 2020). The DOC yields from both horizons are comparable to soil carbon loss via microbial decomposition as measured in permafrost soil incubation experiments (Elberling et al., 2013; Schädel et al., 2014). For instance, after 1 year of incubation at 5°C, carbon loss in upper organic soils averaged 6%, while loss in mineral soils was under 5% (Schädel et al., 2014). Therefore, the export of soil DOC may represent a critical component of the Arctic ecosystem carbon budget. In field conditions, factors like temperature variation and changing flow rates may

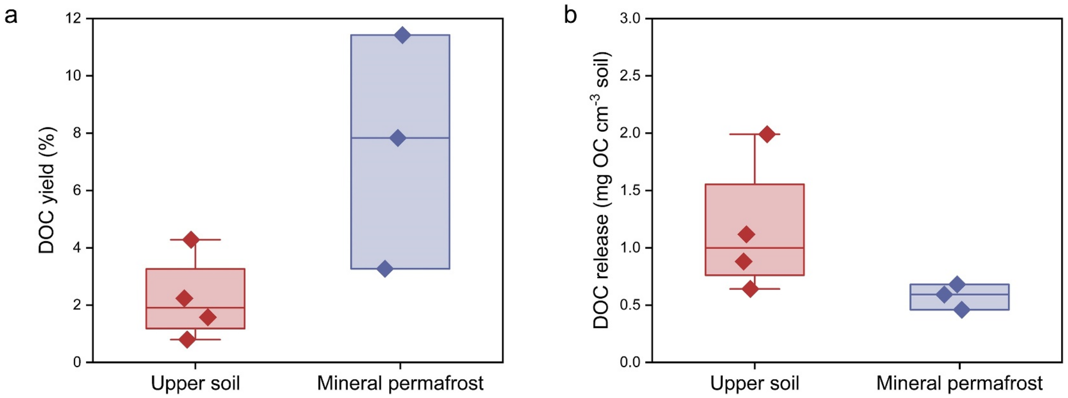

Figure 1. Dissolved organic carbon (DOC) released from different soil horizons in artificial rainwater leaching experiments. (a) Box and whisker plots of DOC yield from different soil horizons. (b) Box and whisker plots of DOC release from different soil horizons. Boxes denote the first and third quartiles on either side of the median.

affect DOC yield and should be systematically studied in the future, especially given rising Arctic temperatures and subsequent disturbances in hydrological conditions (Lafrenière & Lamoureux, 2019; Walsh, 2014).

To better compare the potential export of DOC from different soil horizons, we further define a parameter, DOC release (mg OC cm^{-3} soil), by dividing the total amount of leachable OC by the volume of soil samples (Section 2, Table S1 in Supporting Information S1). In general, DOC releases from upper active-layer soils are greater than those from mineral permafrost soils (Figure 1b). Although mineral permafrost exhibits lower DOC releases per unit volume, its substantial thickness may result in greater cumulative DOC release as permafrost thaws. For instance, the observed maximum depth of the upper organic-rich (TOC > 5%) active layer at the EML site is 1 m (Hutchings et al., 2019) and can be much less in other regions (Michaelson & Ping, 2003; Moni et al., 2015), whereas Yedoma permafrost can be 30–40 m thick or even more (Kanevskiy et al., 2011). While thaw depths are still rather stable in the continuous permafrost zone, deepening of the active layer has already been observed in the pan-Arctic region (e.g., discontinuous permafrost zone), with average deepening rates ranging from 0.0 to 1.3 cm per year in the Arctic and 0.2–0.9 cm per year for Alaska (Smith et al., 2022). In addition, extended thermokarst activities also speed up the exposure and accessibility of deep mineral permafrost (Farquharson et al., 2016; Kokelj & Jorgenson, 2013). As Arctic permafrost continues to destabilize, DOC release from deeper mineral permafrost could potentially match or even surpass that from upper active layers. This potential shift in DOC sources may significantly alter the lability of DOC from soils.

3.2. Changes of DOC During Vertical Percolation

In the percolation experiment, mixed upper soil leachates were used to leach deeper mineral permafrost and investigate DOC changes during vertical percolation (Section 2, Figure S3 in Supporting Information S1). The DOC from mixed upper soil leachate is referred to as $DOC_{U\text{-mix}}$, while the DOC collected from mineral permafrost after percolation is called $DOC_{P\text{-U-mix}}$. The aforementioned $DOC_{P\text{-AR}}$ collected from mineral permafrost in the artificial rainwater leaching experiment was used as a control to quantify the DOC release induced by water movement. Theoretically, without any retention or addition of OC in the percolation process, $DOC_{P\text{-U-mix}}$ should be the sum of $DOC_{U\text{-mix}}$ and $DOC_{P\text{-AR}}$. Our experiments show that values of $DOC_{P\text{-U-mix}}$ are lower than the sum of $DOC_{U\text{-mix}}$ and $DOC_{P\text{-AR}}$ (Figures S5a, S6a, and S7a in Supporting Information S1), indicating retention or loss of DOC during vertical percolation. To better quantify this change, we define ΔDOC as $DOC_{P\text{-U-mix}} - (DOC_{U\text{-mix}} + DOC_{P\text{-AR}})$ (Methods). ΔDOC values are negative in most collections (Figure 2), with the lowest ΔDOC values appearing at the beginning of the experiment, indicating the most intense retention of upper leachates at the early stage of the percolation. Our results align with the retention phenomenon in temperate soils (Guggenberger & Kaiser, 2003; Kalbitz & Kaiser, 2008) and support our hypothesis that deeper mineral permafrost could act as an "internal" carbon sink for upper soil DOC. Potential loss of OC via biochemical activities is likely very limited by controlled experimental processes. The soil samples were all freeze-dried before experiments, and mixed upper soil leachates were kept in an ice-water mixture (0°C) to control temperature during percolation. Moreover, each percolation experiment lasted 13–14 hr, with overnight

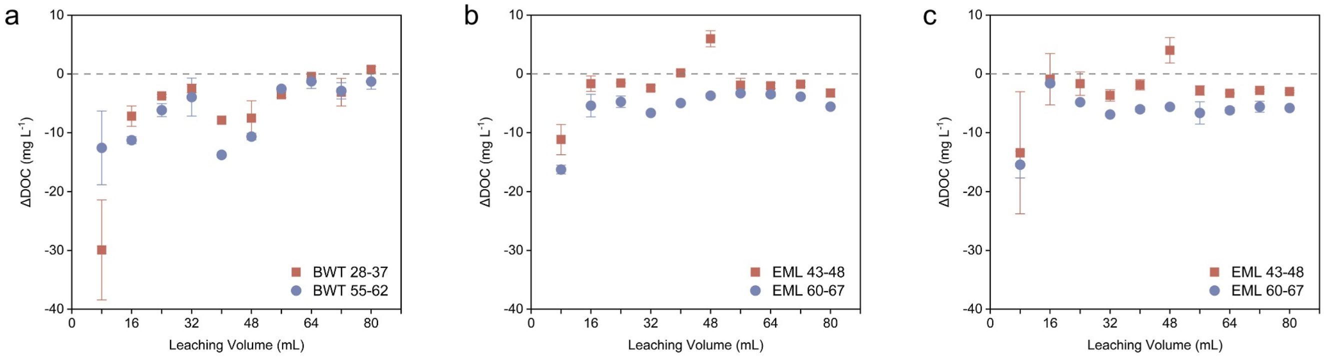

Figure 2. The amount of organic carbon retention (ΔDOC) during continuous collections in vertical percolation experiments of permafrost samples. (a) BWT 182–191, (b) EML 141–147, and (c) EML 259–267. Each mineral permafrost sample was leached using two mixed upper soil leachates (orange and blue).

storage at 4°C; collections were conducted just over an hour and immediately refrigerated, minimizing microbial respiration based on a recent study on C loss of fresh permafrost (Tanski et al., 2019). Photochemical decomposition was also controlled by wrapping all transparent parts of the setup in aluminum foil.

To gain a deeper understanding of the “internal” carbon sink in mineral permafrost, we calculate two parameters: OC retention (%) by dividing retained OC by the OC in mixed upper leachates, and normalized OC retention (mg OC cm^{-3} soil) by dividing retained OC by soil weight and multiplying by bulk density (Methods, Table 1). The results show that OC retention ranges from 11.17% to 46.42%, indicating that a large fraction of DOC from upper soils can be retained by freshly thawed deep mineral soils. Meanwhile, the normalized OC retention ranges between 0.07 and 0.21 mg OC cm^{-3} soil. While the presence of ice in deep mineral soil may influence bulk density measurements and consequently alter the parameter ranges presented, the retention effect's significance remains well-established. As thaw depth continually increases, it is reasonable to suspect that a majority of DOC from the upper organic-rich soils could potentially be retained in mineral permafrost. Our findings suggest that focusing solely on the DOC export across different horizons, while overlooking the retention effect and interactions between soil horizons, may be problematic.

Although we observed DOC retention in mineral permafrost during leaching experiments, the long-term stability of retained OC remains uncertain. The retained OC could potentially be decomposed by microbial activities under dynamic redox conditions (Lin et al., 2021; McDonough et al., 2022) or primed by fresh carbon inputs during subsequent flushing events (Bernard et al., 2022; He et al., 2023). Conversely, mineral associations may promote long-term OC stabilization (Gentsch et al., 2018; Liu et al., 2022; Martens et al., 2023). These competing dynamics represent a key knowledge gap for future research. Critically, field hydrological conditions (e.g., water table fluctuations, flow path variations) can substantially affect DOC release, transport, and export via groundwater systems (Groeneveld et al., 2020; Mohammed et al., 2022; S. Wang et al., 2024; Wen et al., 2022). Future studies should therefore evaluate the long-term lability of retained OC and its comprehensive impacts on Arctic carbon cycling.

Table 1
Organic Carbon Retention Capacity of Mineral Permafrost Using Different Upper Soil Leachates

Sample ID	Leachate	$\mathrm{DOC}_{\text{U-mix}}$ (mg L^{-1})	OC retention (%)	Normalized OC retention (mg OC cm^{-3} soil)
BWT 182-191	BWT 28-37	13.65	46.42 ± 12.33	0.14 ± 0.04
	BWT 55-62	38.22	15.71 ± 0.66	0.13 ± 0.01
EML 141-147	EML 43-48	17.46	11.17 ± 2.50	0.07 ± 0.02
	EML 60-67	25.13	22.93 ± 0.93	0.21 ± 0.01
EML 259-267	EML 43-48	17.46	16.80 ± 12.47	0.10 ± 0.07
	EML 60-67	25.13	25.66 ± 0.61	0.21 ± 0.00

3.3. Alterations of DOC Chemical Composition During Vertical Percolation

In addition to DOC quantity, we also examined the optical properties of leachates during the percolation experiment to assess the retention effect on the chemical composition of DOC. The DOC concentrations of leachates collected from mineral permafrost after percolation ($DOC_{P\text{-}U\text{-}mix}$) show exponential-like decreases as leaching volume increases (Figures S4–S7 in Supporting Information S1). During the initial phase of the experiment, the chemical composition of $DOC_{P\text{-}U\text{-}mix}$ is predominantly governed by DOC released from mineral permafrost through water movement ($DOC_{P\text{-}AR}$). In contrast, during the intermediate and late experimental stages, hydrological-mediated DOC release from mineral permafrost become negligible (Figure S4a in Supporting Information S1). Consequently, observed variations in optical properties during these later stages can be attributed to chemical transformation occurring during the vertical percolation process.

$SUVA_{254}$ is commonly used to indicate the aromaticity of dissolved organic matter (DOM) (Weishaar et al., 2003), while a_{350} is an indicator for dissolved lignin phenol and chromophoric dissolved organic matter (Hernes & Benner, 2003; Spencer et al., 2008). During the intermediate and late stages of vertical percolation, $SUVA_{254}$ and a_{350} values of mineral permafrost leachates are generally lower than those of added upper soil leachates (Figures S5b, S5c, S6b, S6c, S7b, and S7c in Supporting Information S1), indicating a decrease in the aromaticity of DOC as it percolates through mineral permafrost. This preferential retention of aromatic and/or chromophoric components by the mineral permafrost during vertical percolation is consistent with other temperate studies (Sanderman et al., 2014; M. Wang et al., 2019), which indicates that lignin-, aromatic-, and humic-like compounds are mainly retained by fine mineral particles. A conceptual model of DOC cycling in soil (Kaiser & Kalbitz, 2012) proposes that, in addition to microbial processing, fractional sorption and co-precipitation of plant-derived compounds in mineral soils play a key role in driving the compositional changes within soil columns. This suggests that retention of DOC in mineral soils may be largely related to the retention of aromatic components.

Our controlled artificial rainwater experiment showed higher $SUVA_{254}$ in leachates from upper soils than in those from thawed mineral permafrost (Figure S4 in Supporting Information S1), suggesting more aromatic and less aliphatic components in upper soils, consistent with observations in other Arctic soils (Fouché et al., 2020; MacDonald et al., 2021; Xu et al., 2009) and temperate regions (Bu et al., 2010; Han et al., 2016; Kaiser & Kalbitz, 2012). This pattern is likely driven by advanced humification of abundant surface litter, which enriches aromatic compounds (Kaiser & Kalbitz, 2012), coupled with their preferential retention through mineral adsorption/precipitation (e.g., Fe/Al hydroxides) in upper horizons (El-sayed et al., 2019; Riedel et al., 2013; Y. Wang et al., 2017). Meanwhile, compounds with weaker binding affinities (e.g., carbohydrates and nitrogen-rich compounds) could be transported to deeper soil horizons (Kaiser & Kalbitz, 2012). Aliphatic compounds are generally more labile than aromatic compounds and thus more susceptible to microbial degradation (Li et al., 2018; Peters et al., 2005; Textor et al., 2019). Consequently, future increased release of DOC from thawing mineral permafrost and preferential retention of aromatic DOC from upper soil layers could potentially enhance the overall lability of exported soil DOC into aquatic systems.

4. Conclusions and Implications

Our leaching experiments demonstrate high DOC yields from both active-layer organic soils and mineral permafrost, with higher release from the latter. The vertical transport of soil DOC involves both retention of upper soil DOC and alteration of chemical composition in mineral soils (Figure 3). These findings have important implications for future soil incubation studies, as leaching processes can remove substantial amount of soil OC, thereby affecting the lability of remaining solid-phase OC and subsequent greenhouse gas emissions. Furthermore, DOC retention in mineral soils may represent a critical mechanism that should be incorporated into large-scale DOC flux models and estimates (e.g., Connolly et al., 2020; Mohammed et al., 2022), as it affects both current Arctic DOC export estimates and future projections under increasing permafrost thaw. However, the long-term stability of the retained OC remains uncertain and requires targeted investigation. The observed chemical fractionation during vertical transport—particularly the preferential retention of aromatic compounds—acts as a natural “filter” that may enhance the lability of exported Arctic soil DOC. The retention mechanism could partially explain the lower aromaticity of summer riverine DOC (Mann et al., 2016; Striegl et al., 2005) when increased water flux through mineral-rich active layers occurs. Collectively, these findings highlight the pressing

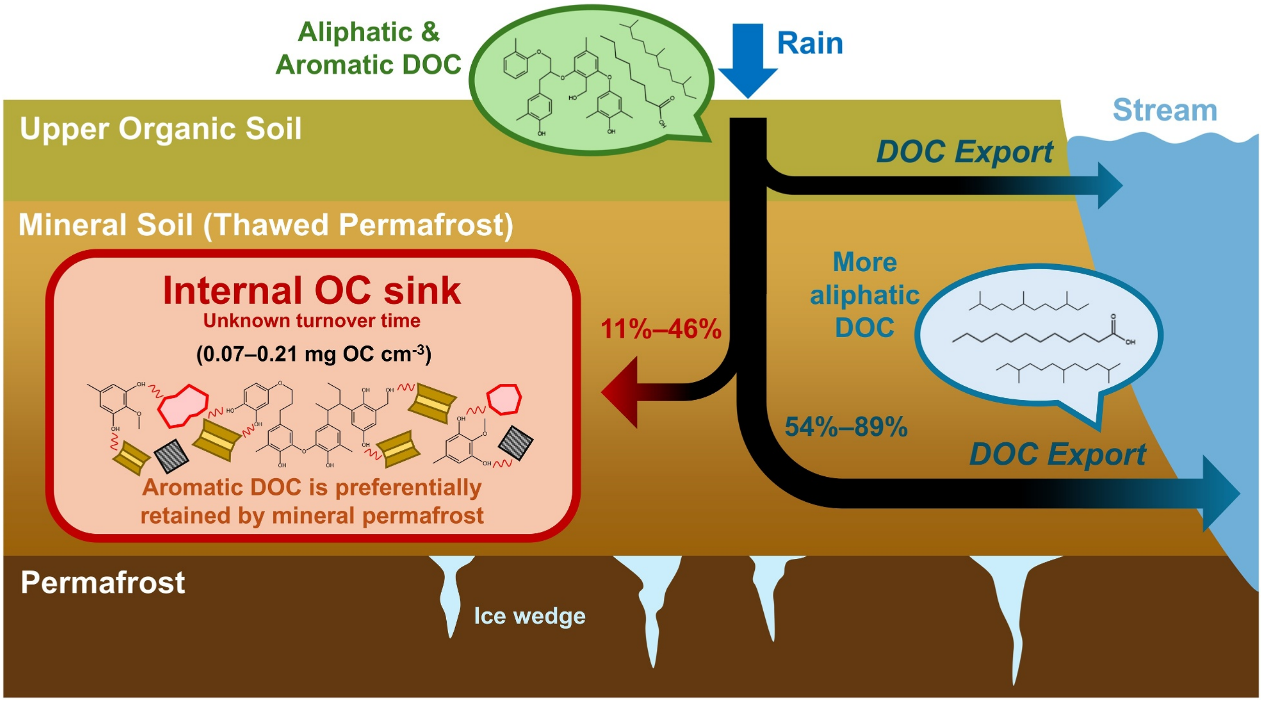

Figure 3. Conceptual model for the mobilization of soil dissolved organic carbon (DOC). A proportion of upper soil DOC is retained in thawing mineral permafrost with some chemical alteration.

need to understand DOC dynamics in thawing permafrost to improve predictions of Arctic carbon-climate feedbacks.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The chemical analysis data used in this manuscript are available at Zenodo (Zhang & He, 2025).

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