Review article: ~~A systematic review of t~~Terrestrial dissolved organic carbon in northern permafrost

Liam Heffernan[1], Dolly N. Kothawala[1], Lars J. Tranvik[1]

[1]Limnology/Department of Ecology and Genetics, Uppsala University, Norbyvägen 18D, Uppsala 75236, Sweden

Correspondence email: liam.heffernan@ebc.uu.se

Abstract

As the permafrost region warms and permafrost soils thaw, vast ~~pools~~ stores of soil organic carbon (C) become vulnerable to enhanced microbial decomposition and lateral transport into aquatic ecosystems as dissolved organic carbon (DOC). The mobilization of permafrost soil C can drastically alter the net northern permafrost C budget. DOC entering aquatic ecosystems becomes biological available for degradation as well as other types of aquatic processing. However, it currently remains unclear which landscape characteristics are most relevant to consider in terms of predicting DOC concentrations entering aquatic systems from permafrost regions. Here, we conducted a systematic review of 111 studies relating to, or including, concentrations of DOC in terrestrial permafrost ecosystems in the northern circumpolar region published between 2000 – 2022. We present a new permafrost DOC dataset consisting of 2,276 DOC concentrations, collected from the top 3 m in permafrost soils across the northern circumpolar region. Concentrations of DOC ranged from 0.1 – 500 mg L^{-1} (median = 41 mg L^{-1}) across all permafrost zones, ecoregions, soil types, and thermal horizons. DOC concentrations were greatest in the sporadic permafrost zone (101 mg L^{-1}) while lower concentrations were found in the discontinuous (60 mg L^{-1}) and continuous (59 mg L^{-1}) permafrost zones. The highest median DOC concentrations of 66 mg L^{-1} and 63 mg L^{-1} were found in coastal tundra and permafrost bog ecosystems, respectively. Coastal tundra (130 mg L^{-1}), permafrost bogs (78 mg L^{-1}), and permafrost wetlands (57 mg L^{-1}) had the highest DOC concentrations in the permafrost lens, representing a potentially long-term store of DOC. Other than in Yedoma ecosystems, DOC concentrations were found to increase following permafrost thaw and were highly constrained by total dissolved nitrogen concentrations. This systematic review highlights how DOC concentrations differ between organic- or mineral-rich deposits across the circumpolar permafrost region and identifies coastal tundra regions as areas of potentially important DOC mobilization. The quantity of permafrost-derived DOC exported laterally to aquatic ecosystems is an important step for predicting its vulnerability to decomposition.

1. Introduction

Persistent freezing temperatures since the late Pleistocene and Holocene has led to the accumulation and preservation of 1,460 – 1,600 Pg of organic carbon (C) in northern circumpolar permafrost soils (Hugelius et al., 2014; Schuur et al., 2018). However, in recent decades, there has been an amplified level of warming at high latitudes, occurring at four-times the speed of the global average (Rantanen et al., 2021). This is leading to widespread and rapid permafrost thawing which is predicted to continue under various future climate scenarios (Olefeldt et al., 2016). Under the high C emissions representative concentration pathway (RCP8.5), 90% loss of near-surface permafrost is projected to occur by 2300, with the majority of loss occurring by 2100 (McGuire et al., 2018). Increasing temperatures and widespread thaw exposes permafrost C to heterotrophic decomposition, potentially leading to enhanced emissions of greenhouse gases to the atmosphere in the form of carbon dioxide (CO_2; Schuur et al., 2021) and methane (CH_4; Turetsky et al., 2020). ~~Alternatively~~Additionally, previously frozen soil organic carbon may be mobilized into the aquatic network as dissolved organic carbon (DOC), the quantity and quality of which will likely depend on local and regional hydrology, and landscape characteristics (Tank et al., 2012; Vonk et al., 2015). At high latitudes (>50°N), lakes and rivers of various sizes cover 5.6% and 0.47% of the total area, respectively (Olefeldt et al., 2021), and the landscape C balance at these high latitudes is highly dependent on aquatic C processing (Vonk & Gustafsson, 2013). The increased leaching of recently thawed DOC from permafrost soils will ~~not only~~ increase the currently estimated 25 – 36 Tg DOC year^{-1} exported into the freshwater system, and subsequently~~-~~ into the Arctic Ocean (Holmes et al., 2012; Raymond et al., 2007). It may~~, but~~ ~~will~~ also ~~likely~~ lead to enhanced greenhouse gas emissions from freshwater ecosystems (Dean et al., 2020). However, uncertainty remains as to which terrestrial ecosystems contain the highest concentrations of DOC, ~~are likely to contribute the highest concentrations of~~ laterally transport the greatest quantities of ~~ed permafrost~~ DOC, and ~~of this, which is expected to contribute~~represent the store of ~~the~~ DOC most vulnerable to mineralization.

Globally, DOC concentrations have been shown to vary across biomes, and spatial and temporal scales (Guo et al., 2020; Langeveld et al., 2020). It has been suggested that at such macro scales hydrology, climate, vegetation type, and soil type be important drivers of DOC cocnentrations (Langeveld et al., 2020). Hydrology and climate are important factors shaping ecosystem structure and function in permafrost regions (Andresen et al., 2020; Wang et al., 2019), which in turn influences the spatial distribution of vegetation and soil types. Vegetation type has been shown to be the most important driver of DOC concentrations in Arctic lakes (Stolpmann et al., 2021). Carbon uptake by vegetation, via gross primary production, and SOC stocks in the permafrost region have both been shown to vary across vegetation and soil types (Ma et al., 2023; Hugelius et al., 2014). This variability across vegetation and soil types has important implications for DOC production, which is associated with plant inputs (Moore & Dalva, 2001) and the decomposition and solubilization of SOC due to soil microbial activity (Guggenberger & Zech, 1993). In permafrost soils, the majority of this production is likely to occur near the soil surface as the microbial production of DOC via input of plant-derived labile substrates has been shown to decrease with depth (Hultman et al., 2015; Monteux et al., 2018; Wild et al., 2016) and 65 – 70 % of the SOC store is found in the top 3 m (Hugelius et al., 2014). The spatial distribution discrepancies observed in DOC concentrations from global assessment efforts (Guo et al., 2020; Langeveld et al., 2020) may be reduced for the circumpolar permafrost region by improving understanding of DOC concentrations in the top 3 m across ecosystem types.

The contribution of mineralized permafrost C to atmospheric CO_2 and CH_4 balances, known as the permafrost C feedback (Schaefer et al., 2014), remains poorly constrained due to uncertainty of the magnitude and location of permafrost C emissions (Miner et al., 2022). Previous studies have highlighted that tThe mineralization and lateral transport of DOC, i.e., mobilization, represents a source of terrestrial permafrost C that can potentially play an important role in both terrestrial and aquatic biogeochemical cycles (Hugelius et al., 2020; Parmentier et al., 2017; Schuur et al., 2022). However, none have quantified DOC mobilization across the permafrost region. and is thus Inclusion of DOC mobilization in attempts to determine the permafrost climate feedback (Schaefer et al., 2014), may reduce current uncertainty in the magnitude and location of permafrost C losses (Miner et al., 2022), particularly as permafrost thaws. an important fraction of the permafrost C feedback. Warming of near surface permafrost causes widespread thawing (Camill, 2005; Jorgenson et al., 2006), which can lead to drastic changes in hydrology, vegetation, and soil carbon dynamics (Liljedahl et al., 2016; Pries et al.,

Commented [LH1]: 4 questions are
1. which ecosystem has the most doc
2. what are the rates of mobilization in each ecosystem
3. what are the major controls on doc conc and mobilization
4. how does mobilization respond to thawing

So then the structure for two paragraph should be
Flow should be

where DOC comes from and what are the controls on this formation and degradation (q1 and 3)
transition this into how different ecosystems are in the region, including climatic differences in where ecosystems are found (q1 and 2) - what we know about this from previous work and syntheses (including outside perm region) - can introduce the idea that syngenetic permafrost can have high losses of oc (alaska peat, alaska soil-schuurs group, and yedoma)
Move into doc mobilization, particularly lateral transport (q2 and 3)
Finish with how thawing influences hydrology and lateral flow - implications for permafrost carbon feedback (q4)

2012; Varner et al., 2022), thus impacting both DOC production and mobilization. Several studies have demonstrated that DOC has the potential to be rapidly degraded and mineralized following thermokarst formation (Burd et al., 2020; Payandi-Rolland et al., 2020; Wickland et al., 2018), particularly in higher latitude ecosystems (Ernakovich et al., 2017; Vonk et al., 2013). However, few have compared this lability across ecosystems (Abbot et al., 2014; Fouche et al., 2020; Textor et al., 2019) and less have done so across the permafrost region (Vonk et al., 2015). Determining the ecosystems with the greatest store of DOC that is readily mineralized upon thermokarst formation represents a potentially important step in reducing uncertainty in the permafrost climate feedback. ~~When permafrost is present, the lateral transport of DOC is restricted to flow paths within the unfrozen, organic rich active layer (Woo, 1986). Deeping of the seasonally thawed active layer due to top-down permafrost thaw can lead to longer flow paths for DOC, allowing for enhanced decomposition or adsorption to mineral particles, resulting in reduced DOC export (Kicklighter et al., 2013; Striegl et al., 2005). Alternatively, thermokarst formation can affect the entire soil profile, leading to surface inundation, and shifting ecological conditions and vegetation communities associated with greater DOC production (Turetsky et al., 2007). This can cause greater hydrological connectivity, resulting in increased runoff in permafrost peatlands (Connon et al., 2014) or increased connectivity to regional hydrology through thermo-erosion gullies or thaw slumps (Kokelj & Jorgenson, 2013) in tundra ecosystems. Permafrost landscape dynamics, including the mode of permafrost thaw and ecological conditions present following thaw, will play a key role in the biogeochemical and ecohydrological processes that constrain DOC mobilization, i.e., export and mineralization upon export. The freshwater DOC pool represents a mix of C derived from a variety of ecosystem types and sources, and the ecological conditions of each source will have a significant impact on the quantity and quality of this mobilized DOC. Determining the relative contribution and impact on mineralization of these DOC sources represents a potentially important step in reducing uncertainty in the permafrost climate feedback.~~

Here, we conduct a systematic review of the literature and compiled 111 studies published between 2000 – 2022 on DOC concentrations in the top 3 m of soil in terrestrial ecosystems found in the northern circumpolar permafrost region. Our aim was to build a database to assess the concentration and mobilization of DOC across terrestrial permafrost ecosystems. We used this database to address the following hypotheses; (i) the highest DOC concentrations would be found in organic rich wetland ecosystems; (ii) disturbance would lead to increased export and biodegradability of DOC; and (iii) the most biodegradable DOC would be found in Yedoma and tundra ecosystems. A quantitative assessment of studies pertaining to DOC concentrations in permafrost soils can identify evidence-based recommendations for future topics, standardisation of methods, and areas of research to improve our understanding on terrestrial and aquatic biogeochemical cycling in northern permafrost regions. Our database contains ancillary data describing the geographical and ecological conditions associated with each DOC concentration, allowing us to reveal patterns in DOC concentrations and lability measures for 562 sampling sites across multiple ecosystem types and under varying disturbance regimes. This study represents the first systematic review of DOC concentrations within terrestrial permafrost ecosystems found in the circumpolar north. As such, it provides unique and valuable insights into identifying ~~ecoregions~~ecosystems~~, or landscape characteristics,~~ associated with the highest DOC concentrations, and thus ~~regions~~ ecosystems with the greatest potential for DOC mobilization. ~~We hypothesized that (i) the highest DOC concentrations would be found in organic rich wetland ecosystems, (ii) disturbance would lead to increased export and biodegradability of DOC, and (iii) the most biodegradable DOC would be found in Yedoma and tundra ecosystems.~~

Commented [LH2]: In intro add in text about how some studies show increased lability whereas other show the opposite, talks about fresh inputs but also the sorption (or desorption) to minerals following thaw or export to aquatic network

2. Methods

This systematic review used a methodological framework proposed by Arksey & O'Malley (2005) and follows five steps: 1) develop research questions and a search query; 2) identify relevant studies; 3) study selection; 4) data extraction; and 5) data analysis, summary, and reporting. The literature search was guided by four research questions: 1) what are the concentrations of DOC found in terrestrial ecosystems across the northern circumpolar permafrost region?; 2) what are the rates of export and/or degradation (mobilization) of DOC within these ecosystems?; 3) What are the major controls on DOC concentrations and rates of mobilization?; and 4) how are concentrations and mobilization rates impacted by thermokarst formation? Mobilization rates represent DOC loss and include specific discharge of DOC (g DOC m^{-2}), export rate of DOC per day (g C m^{-2} day^{-1}) and per year (g C m^{-2} $year^{-1}$), and biodegradable DOC (BDOC; %).

2.1 Literature Search

Based on *a priori* tests, we used the following search query string to find papers using information found in their title, abstract, and keywords: (”dissolved organic carbon”) AND (permafrost OR thermokarst OR "thaw slump") AND (soil OR peat) AND (export OR degrad* OR decomposition OR mineralization). We used Web of Science, Science Direct, Scopus, PubMed, and Google Scholar to generate a database of tier 1, peer-reviewed articles published between 2000 – 2022. The search function on Science Direct does not support the use of wildcards such as “*”, so “degrad*” was changed to “degradation”. We removed duplicate references found across multiple databases using Mendeley© referencing software (v1.17.1, Mendeley Ltd. 2016). ~~Once this initial database was complied, w~~We used the same search query string as above to search for ~~additional~~ articles on the first 15 pages of Google Scholar. This resulted in the addition of a further 150 articles to be included in our systematic screening process.

2.2 Systematic Screening of Peer-Reviewed Publications

The selection of relevant studies was comprised of inclusion criteria and relevance screening in three steps. In the first step we placed limits on initial study searches in the electronic databases mentioned above. Studies were included in the review if they were primary research, published in English, and published between 2000 – 2022 (Table 1). Only quantitative studies conducted in terrestrial ecosystems within the northern circumpolar permafrost region, as defined by Brown et al., (1997), and reporting DOC concentration and mobilization rates were included. Studies not meeting these criteria were eliminated and the remaining studies proceeded to the second screening step.

Table 1. Summary of criteria used to identify suitable studies in the preliminary screening stage

	Inclusion criteria	**Exclusion criteria**
Timeline	Study published between 2000 – 2022	Study published prior to 2000
Study type	Primary research article published in peer-reviewed journal using quantitative methods	Thesis/dissertations and secondary research studies (reviews, commentaries, editorials)
Language	Published in English	Studies published in other languages

Region	Conducted within the northern circumpolar permafrost region	Conducted outside of the northern circumpolar permafrost region
Outcome	Studies on DOC concentration, export or degradation in permafrost environments	Studies not on DOC concentration, export or degradation in permafrost environments

In the second step, the primary relevance of articles was screened, based on article titles, abstracts, and keywords, and the eligibility criteria provided in Table 2. Studies deemed irrelevant were eliminated and the remaining studies proceeded to the third and final screening step, or secondary screening stage, which was based on was based on more specific eligibility criteria (Table 2) applied to the full text.

Table 2. Primary and secondary relevance screening tools. Primary screening tool used in the article title, abstract, and keyword screening stage. Secondary screening tool used in full-text screening stage

Screening stage	Screening questions	**Response details**
Primary	Does the study involve quantitative data collected from a permafrost environment?	Yes – reports on quantitative data collected from a permafrost environment No – does not report on the above
Primary and Secondary	Is the study region within the northern circumpolar permafrost region?	Yes – reports on quantitative data (including field observations and lab data) collected from the circumpolar permafrost environment. No – study region is not in the northern circumpolar permafrost regions; other examples could be mountainous permafrost or Tibetan plateau
Primary and Secondary	Is the article in English and NOT a review, book chapter, commentary, correspondence, letter, editorial, case report, or reflection?	Yes – study is in English and is a primary research article that includes quantitative studies (field and lab based), including model-based research as it relies on observational data.* No – study is not in English and/or is a review, book, editorial, working paper, commentary, conference proceeding, supplementary text, or qualitative study which does not address outcomes relevant to this review

Primary and Secondary	Does the study involve the concentration, export or degradation of terrestrially derived DOC?	Yes – reports on terrestrial DOC concentration, export, or degradation, including concentrations and characterization No – does not report on terrestrial DOC concentration, export, or degradation
Secondary	Is the article in English, longer than 500 words, and published between 2000 - 2022?	Yes – study is published between 2000 – 2022 No – study is published prior to 2000

*For model-based studies, the original field/lab data used to parametrise or develop the model was used. If this data was taken from previously published work, then those studies were used and the model-based study removed.

2.3 Database compilation

A database with reported DOC concentrations and mobilization rates i.e., rates of either DOC export or degradation, was compiled using data from all studies that were deemed relevant following the study selection phase. The database was compiled to compare DOC concentrations and mobilization rates between different sites. We define a site as an area where either soil, water, or ice samples were taken from that has similar vegetation composition, water table position, permafrost regime, and was either disturbed or pristine. Site descriptions were derived from the text of each study. Where possible, individual daily measurements of DOC concentrations and mobilization rates were taken. When replicates of the same daily measurement were provided, we used the mean of those replicates, which was relevant for 10 studies within the database, representing 72 DOC concentrations. All data was extracted from data tables, text, supplementary material, or extracted from data figures using WebPlotDigitizer (https://automeris.io/WebPlotDigitizer).

All studies reported measuring DOC concentrations collected from either open-water, pore water, ice, or soil using a median filter pore size of 0.45 μm with first and third quartiles pore size of 0.45 and 0.7 μm. Measurements from all 12 months of the year were included in the database with the majority occurring during the growing season (May – August), a small portion during the non-growing season, and the remaining sampling times were either not reported or are averages over multiple sampling occasions. We included data from studies that were both field and lab based. However, any data where a treatment was applied was excluded, except for temperature treatments during incubation experiments when assessing the biodegradability of DOC. When lab-based studies included an incubation, only Day 0 DOC concentrations were used when comparing DOC concentrations across studies. We chose to remove any DOC concentrations from samples taken below 3 m depth, which represented 3% of all DOC measurements. These measurements were removed for better comparability with the current best estimation of soil organic carbon stocks within the northern circumpolar permafrost zone (Hugelius et al., 2014). We also removed any DOC concentrations greater than 500 mg L^{-1}, which represented 2% of all DOC concentrations. Samples that were above 500 mg L^{-1} and were sampled below 3 m represented 1% of all DOC concentrations.

Site averaged daily DOC concentrations (mg L^{-1}) and mobilization rates were estimated from the average concentration and mobilization rates measured within a single day or sampling occasion. Repeated measurements at a site, either over the growing season or multiyear measurements, were treated as an individual estimate of DOC concentrations and mobilization rates. Other continuous variables that were similarly estimated include soil moisture, water table position, organic layer depth, active layer depth, bulk density of soil, soil carbon content (%), soil nitrogen content (%), carbon:nitrogen, pH, electrical conductivity (μS cm^{-1}), specific UV absorbance at 254 nm (SUVA; L mg C^{-1} m^{-1}), total dissolved nitrogen (mg L^{-1}), nitrate (mg L^{-1}), ammonium (mg L^{-1}), chloride (mg L^{-1}), calcium (mg L^{-1}), and magnesium (mg L^{-1}). The aromatic content of organic matter is positively correlated with SUVA (Weishaar et al., 2003), with high SUVA values being used as an indication of high aromatic content (Hansen et al., 2016). Ratios of C:N have been shown to be a good proxy for decomposition (Biester et al., 2014), where high C:N values indicate higher decomposition. Mean annual temperatures and precipitation, sampling depth, filter size, the number of days over which sampling took place, how many years following disturbance measurements were taken were also recorded. Several continuous variables other than those mentioned above were also recorded in the database, but not used for analysis if they represented < 20% of the database. We chose 20% as the cut-off point for use in comparison of the relationship between DOC concentrations and mobilization with other site continuous variables.

Categorical variables included in the database were site location within the permafrost zone (continuous, discontinuous, sporadic; Brown et al., 1997) and ecoregion (arctic tundra, sub-arctic tundra, sub-arctic boreal, and continental boreal; ~~(~~Olson et al., 2001). We included site surface permafrost conditions (present or absent), the thermal horizon layer sampled (active layer, permafrost, permafrost free, water, and thaw stream), and if present what type of disturbance occurred at the site (fire, active layer thickening, thermokarst terrestrial, or thermokarst aquatic). Active layer represents the seasonally unfrozen soil layer above the permafrost layer. Permafrost Lens represents the permanently frozen (below 0 °C) layer. Permafrost lens DOC concentrations are determined from soil and pore water within the permafrost layer and extracted via frozen cores, whereas active layer samples are taken from soil cores or porewater that are unfrozen at the time of sampling. Thaw Stream represents flowing surface waters following permafrost thaw. Permafrost Free represents areas that are not underlain by permafrost. We also included the soil class found at the site (Histel, Histosol, Orthel, and Turbel; USDA, 1999) and whether the DOC was from the organic or mineral soil. Histosols are organic rich, non-permafrost soils. Histels, Orthels, and Turbels are permafrost-affected soils (Gelisol order). Histels are organic rich, Orthels are non cryoturbated affected mineral soils, and Turbels are cryoturbated permafrost soils. Organic rich Histel and Histosol soils have been previously shown to contain greater SOC stocks in the top 3 m of soil than the mineral rich Orthel and Histel soils (Hugelius et al., 2014). To assess the influence of sampling approach and method of analysis, we included method of DOC extraction (centrifugation of soil sample, leaching and dry leaching of soil, dialysis, grab sample, ice core extraction, potassium sulphate extraction, lysimeter, piezometer, pump, rhizons) and DOC measurement method (combustion, persulphate, photometric, or solid-phase extraction).

Sites were classified according to ecosystem type, and these included coastal tundra, forest, peatland, permafrost bog, permafrost wetland, retrogressive thaw slump, upland tundra, and Yedoma. Ecosystem classification is based on the general site description in the article, the provided ecosystem classification within the article, and site data including vegetation composition, permafrost conditions, and ecoregion. Coastal tundra sites includes typical polygonal tundra features found along the coastline in the permafrost region (Lantuit et al., 2012). Forests include any forested ecosystem, such as a black spruce forest (Kane et al., 2006) or larch forest (Kawahigashi et al., 2011) where the soil is not a wetland soil. Peatlands are sites classified as either fens (Olefeldt and Roulet 2012) or bogs (Olsrund and Christensen 2011) that are within the permafrost domain but are not underlain by permafrost. Permafrost bogs are sites that are bogs and are either underlain by permafrost (O'Donnel et al., 2016) or are thermokarst bogs (Burd et al., 2020) that were previously underlain by permafrost prior to thawing. Permafrost wetlands sites include saturated soils that are underlain by permafrost, or were previously underlain by permafrost prior to permafrost thaw. They contain sampling locations typical of moist acidic tundra (Trusiak et al., 2018), tundra meadows (Tanski et al., 2017), and high-latitude fens (Nielsen et al., 2017). Retrogressive thaw slumps are areas where substantial ground ice degradation leads to thermokarst and the resulting feature contains a retreating headwall (Abbott et al., 2015). Upland tundra sites are high-latitude, non-wetland, mineral soils that include tundra heath (Stutter and Billett 2003) and meadows (Hirst et al., 2022). Yedoma sites include pristine forest, upland tundra, and coastal tundra, as well as retrogressive thaw slumps and other thermokarst features found within the Yedoma permafrost domain (Strauss et al., 2021). The ecosystem classification retrogressive thaw slump only includes these thermokarst features found outside the Yedoma permafrost domain. Each ecosystem type was further classified based on the type of permafrost thaw or thermokarst formation that occurred there. These thaw or thermokarst types included thermokarst bog, thermokarst wetland, active layer thickening, retrogressive thaw slump, exposure, thermo-erosion gully, and active layer detachment.

2.4 Database analysis

All statistical analyses were carried out in R (Version 3.4.4, R Core Team, 2015). We aimed to assess how DOC concentrations differed across study regions and ecosystems. To do this ~~W~~we used Kruskal-Wallis analysis to test for differences in median DOC concentrations among the various ~~categorical variables~~study regions and areas ~~such~~ that included ~~as~~ permafrost zones, ecoregions, soil class, thermal horizon, and ecosystems. Post-hoc comparisons of median DOC concentrations among these categories were performed using pairwise Wilcox test. Within and between each ecosystem type we assessed the differences in DOC concentrations found in different thermal horizons (i.e., active layer and permafrost lens). To do this ~~For regression analysis~~, data was first transformed using a Box Cox transformation and the optimal λ using the

MASS package (Ripley et al., 2019). We then ~~used~~ performed analysis of covariance (ANCOVA) to test for differences in DOC concentrations in different thermal horizons between ecosystem types, while controlling for seasonal effects by including the month in which sampling occurred as the covariate.

Following the assessment of differences in DOC concentrations across these study regions and ecosystems we aimed to assess the influence of extraction and analysis method on DOC concentrations. The aim of this was to determine if extraction and analysis method was having a greater effect on DOC concentrations than study region or ecosystem. To do so we first used ANOVAs and Bonferroni post-hoc tests on linear mixed effects models, that include either extraction method, filter size, or analysis method as a fixed effect and ecosystem type as a random factor, to evaluate significant differences in DOC concentrations between DOC extraction and measurement methods. We then performed Kruskal-Wallis analysis to test for differences in median DOC concentrations among the extraction method, filter size, and analysis method in each permafrost zone, ecoregion, soil class, thermal horizon, and ecosystem. Post-hoc comparisons of median DOC concentrations among these categories were performed using pairwise Wilcox test.

We used partial least squares regression (PLS) ~~to assess~~ when assessing the ~~performance of~~relationship of DOC concentrations with- continuous and categorical variables. We performed this analysis ~~in~~ to determine how the drivers of DOC concentrations across ecosystems ~~predicting~~ may explain the variability in DOC concentrations. Predictor variables were categorized based on their Variable Importance in Projections (VIP) method in the *plsVarSel* package (Mehmood et al., 2012), whereby variables with a score > 0.6 – 1 are deemed to be significant (Chong and Jun 2005). We ran several PLS including predictor variables with a VIP of > 0.6, 0.7, 0.8, 0.9, and 1. The most parsimonious PLS model contained predictor variables with a VIP > 1 and was selected based on the proportion of variability in the predictors explained by the model, significant PLS components, Q^2, and background correlation (Andersen and Bro 2010). PLS was performed using the *pls* package (Mevik & Wehrens, 2007) and we chose to use PLS as it is tolerant of co-correlation of predictor variable, deviations from normality, and missing values, all of which were found within the database. In the PLS ecosystem classes were subdivided into pristine or disturbed (i.e., impacted by permafrost thaw). Pristine sites were further subdivided by the thermal horizon in which the DOC concentrations were measured (active layer and permafrost lens). Sites were split into disturbed and pristine to assess whether disturbances has an impact on DOC concentrations. Pristine sites were divided by their thermal horizon to assess whether DOC concentrations were more positively related to the active layer exposed to both microbial decomposition and fresh annual carbon inputs from surface vegetation, or the permafrost lens.

To evaluate the change in ecosystem DOC concentrations following thermokarst formation, based on all studies from the systematic review, we calculated the response ratio using the *SingleCaseES* package (Pustejovsky et al., 2021). We define thermokarst as the process by which ice-rich permafrost deposits undergo complete thaw, resulting in surface subsidence and the formation of a new, thermokarst feature that is ecological different regarding water table position, redox conditions, and vegetation type, from the preceding pristine ecosystem. Very few studies in our database report DOC concentrations for both pristine and thermokarst affected ecosystem (< 20 %). To include as much data as possible we chose an effect size metric that is unlikely to be influenced by studies with large sample number and variance. The response ratio is;

$$Pristine\ to\ Thermokarst\ Effect\ Response\ ratio = \ln\left(\frac{X_P}{X_T}\right) \qquad \text{Eqn. 1}$$

where X_P = mean DOC concertation of pristine ecosystems and X_T = mean DOC concertation of thermokarst effected ecosystems (Lajeunesse, 2011). This represents the log proportional difference in mean DOC concentrations between thermokarst and pristine ecosystems, where a positive response ratio indicates a decrease in DOC concentrations following thermokarst.

The distribution of the data was inspected visually and with the Shapiro–Wilk test. We tested homogeneity of variances using the *car* package and Levene's test (Fox and Weisberg, 2011). We report DOC concentrations as the median value with uncertainty ~~using~~ as ± the interquartile range ~~(lower, median, and upper quartiles)~~, except for response ratios which we report as ± 95% confidence intervals. We here define the statistical significance level at 5%.

3. Results

3.1 *Database generation*

Our initial search using Web of Knowledge, Science Direct, Scopus, PubMed, and Google Scholar returned a total of 577 unique papers published between 2000 – 2022 that assess the concentrations and rates of mobilization of DOC in terrestrial ecosystems within the northern circumpolar permafrost region. Of these initial 577 studies, 111 remained after the systematic screening process (Table 1 & 2). From these 111 studies we generated our database. The final database of 111 studies contained a total of 3,340 DOC concentrations (mg L^{-1}), with 2,845 DOC concentrations between 0 – 500 mg L^{-1}, found within the top 3 m of permafrost soils from field and lab-based studies (using only Day 0 lab-based DOC concentrations). These concentrations were taken from 562 different sampling locations, representing 8 different ecosystem types (Figure 1; Table S1) across the northern circumpolar permafrost region. All studies except, for one (Olefeldt et al., 2012), reported DOC concentrations.

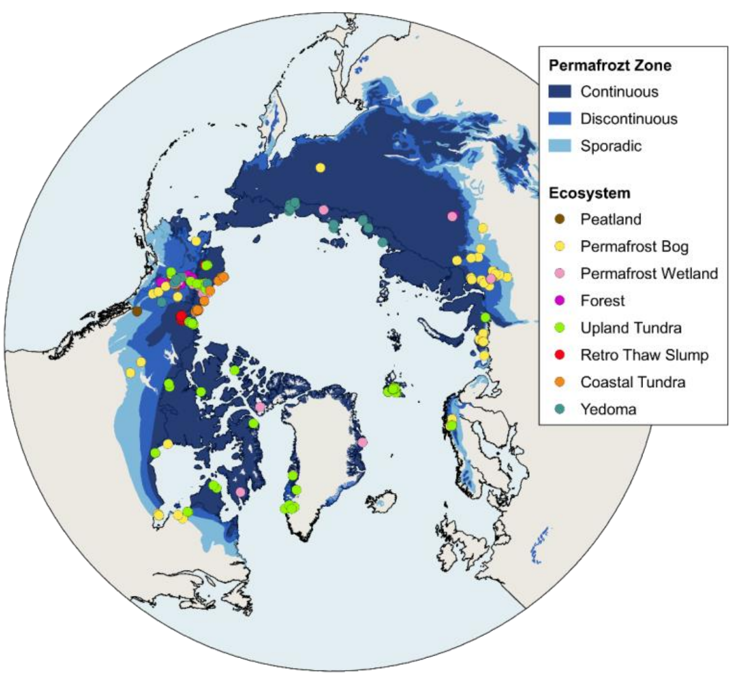

Figure 1. Map of sampling locations where DOC measurements (n=562) from the top 3 m for each ecosystem type. In many cases, the same sampling location was used in multiple studies leading to some overlap, therefore the number of sampling sites included in the data set (562) are not all clearly identifiable from this map. Similarly, several points overlay others even when the ecosystems differ. For a full list of site coordinates please see the database (repository link). Retro Thaw Slump = Retrogressive Thaw Slump. Blue shading represents permafrost zonation (Brown et al., 1997).

The final database contained a considerably lower number of DOC mobilization measurements. The database includes 16 measurements of specific discharge of DOC (g DOC m^{-2}) from 3 studies, 9 export rate of DOC per day (g C m^{-2} day^{-1}) and per year (g C m^{-2} $year^{-1}$) measurements were each found in 2 studies. The number of specific discharge, export of DOC per day, and export of DOC per year measurements combined were <1% of the number of DOC concentration measurements. As such they were not considered for analysis of DOC mobilization. A total of 146 BDOC (%) measurements, 4% of the total number of DOC concentration measurements, were found in 14 studies. These measurements of BDOC were from Yedoma (30:5, number of measurements:studies), Upland Tundra (55:5), Forest (18:3), Permafrost Wetland (12:2), and Permafrost Bog (31:5) ecosystems. Given the low number of other forms of DOC mobilization and relatively comparable spread of BDOC measurements across ecosystem types, we chose to include BDOC measurements in our analysis despite a low total number of measurements compared to DOC concentrations, and we consider this lower sample size during our interpretation of results.

Filter size used in studies ranged from 0.15 – 0.7 µm. The majority of DOC concentrations reported were determined using a filter size of 0.45 µm (58%), 0.7 µm was the second most common filter size (21%), followed by 0.22 µm (14%). We identified eleven different DOC extraction methods in total from both soils and water that are broadly grouped into the following six extraction types; leaching, suction, grab, centrifuged, dialysis, and potassium sulphate (K_2SO_4) extraction. Leaching includes the leaching and dry leaching of soil; suction includes lysimeter, piezometer, pump, and rhizons; grab includes grab samples and ice core extraction; and centrifuged, dialysis, and (K_2SO_4) extraction remain on their own. Suction (42%), leaching (37%), and grab (14%) were the three most common extraction methods across all samples. Leaching and suction extraction methods were used for 66% and 24%, respectively, for all soil samples. For water samples, suction (65%) and grab (31%) were the most common extraction methods. The most common measurement method to determine DOC concentrations was by the combustion method (89%), followed by the persulphate (9%) and photometric (1%) methods.

Filter size used in studies ranged from 0.15 – 0.7 µm. The majority of studies used a filter size of 0.45 µm (1,375 out of 2,845 DOC measurements), 0.7 µm was the second most common filter size (n = 489), followed by 0.22 µm (n = 332) and 0.6 µm (n = 143). Two studies used a filter size of 0.15 µm totalling 18 DOC measurements and remaining studies (n = 12) did not provide a filter size. DOC concentrations were found to differ between different filter sizes (ANOVA: $F_{(4, 2339)} = 22.9$, $p < 0.001$). DOC concentrations from samples filtered using 0.7 µm were lower (median = 11 mg L^{-1}) than 0.45 µm and 0.22 µm filtered samples (median = 53 and 42 mg L^{-1}, respectively). We consider the effects of filter size to be minor. DOC concentrations were found to be significantly different between samples subject to the 11 different extraction methods used (ANOVA: $F_{(10, 2515)} = 21.8$, $p < 0.001$), and between water based and soil (solid) based extraction methods (ANOVA: $F_{(1, 2524)} = 182.1$, $p < 0.001$). Median DOC concentrations of the 4 methods of extraction directly from soils (leaching from soil under field moisture conditions, leached from dried soils, centrifuged soils, and extracted using K_2SO_4) were 57 mg L^{-1}, with upper and lower quartiles of 20 and 120 mg L^{-1}, respectively. The 7 water-based extraction methods had a median DOC concentration of 24 mg L^{-1}, with upper and lower quartiles of 8 and 59 mg L^{-1}, respectively. DOC concentrations differed (ANOVA: $F_{(3, 2515)} = 36.2$, $p < 0.001$) between samples subject to different dissolved organic carbon measurement methods, with median values of 37 and 48 mg L^{-1} for the combustion, and photometric methods, respectively. Median values measured using the persulphate were higher at 97 mg L^{-1}. Combustion was the most common method, accounting for 2,170 DOC concentrations, followed by persulphate (n = 230) and photometric (n = 31). In this study we did not focus on systematically testing the effect of filter sizes, extraction methods, or DOC measurement methods. Our goal was to assess the concentration and mobilization of DOC in terrestrial permafrost ecosystems and the assessment of methods is outside the scope of our study. Rather, we compare DOC concentrations collected from samples using a variety of these methods and

~~suggest that future studies use this information to decide on methods to be consistent with compiled measurements, thus far.~~

3.2 DOC concentrations and study regions

Upon inspection of DOC concentrations in the database, we determined that the data was non-normally distributed. The DOC concentrations were skewed toward the lower end of our 0 – 500 mg L^{-1} range; thus, we report median, upper, and lower quartiles below. Across all studies, within the top 3 m of soil, the median DOC concentration was 41 ± 74 mg L^{-1}~~, with upper and lower quartiles of 12 and 86 mg L^{-1}, respectively~~. DOC concentrations were found to differ among the three permafrost zones (chi-square = 32, df = 2, $p < 0.001$; Figure 2a). The highest median DOC concentrations were found within the sporadic permafrost zone (n = 83; 62 ± 144 mg L^{-1})~~, lower quartile (LQ) and upper quartile (UQ) of 23 and 167 mg L^{-1}, respectively~~. The lowest median of 33 ± 77 mg L^{-1} ~~(LQ and UQ of 11 and 88 mg L^{-1}, respectively)~~ was found in the continuous permafrost zone (n = 1,648), with the greatest density of samples having lower DOC concentrations than observed in the violin plots of both the discontinuous and sporadic (Figure 2a). This change in DOC concertation's along the latitudinal gradient of the permafrost zonation was also seen in the latitudinal gradient associated with ecoregion, where Arctic Tundra and Sub-Arctic Tundra are found at higher latitudes than both boreal ecoregions (chi-square = 78, df = 3, $p < 0.001$; Figure 2b). The highest DOC concentrations were found in the continental boreal (n = 389; 56 ± 56 mg L^{-1}~~; LQ = 24 mg L^{-1}; UQ = 80 mg L^{-1}~~) and Sub-Arctic Boreal (n = 442; 58 ± 97 mg L^{-1}~~; LQ = 20 mg L^{-1}; UQ = 107 mg L^{-1}~~) ecoregions, and lowest in the Arctic Tundra (n = 1,209; 25 ± 75 mg L^{-1}~~; LQ = 9 mg L^{-1}; UQ = 84 mg L^{-1}~~) and Sub-Arctic Tundra (n = 493; 43 ± 61 mg L^{-1}~~; LQ = 15 mg L^{-1}; UQ = 76 mg L^{-1}~~) ecoregions. Inspection of the distribution of DOC concentrations across the ecoregions highlights that the Arctic Tundra ecoregion had the highest density of samples at the lowest DOC concentration (Figure 2b).

These latitudinal differences are also reflected in the observed differences (chi-square = 20, df = 3, $p < 0.001$) in DOC concentrations found within different soil classes. The highest DOC concentrations are found within organic rich Histosol (n = 37; 61 ± 39 mg L^{-1}~~; LQ = 32 mg L^{-1}; UQ = 71 mg L^{-1}~~) and Histel soils (n = 935; 53 ± 72 mg L^{-1}~~; LQ = 16 mg L^{-1}; UQ = 88 mg L^{-1}~~; Figure 2c), with the distribution of the data from these soils types having a higher density at greater DOC concentrations (Figure 2c). Histel and Histosol soils are the main type of permafrost soil found within the sporadic and discontinuous permafrost zone and both boreal ecoregions (Hugelius et al., 2014). Mineral rich Orthels (n = 741; 38 ± 91 mg L^{-1}; LQ = 11 mg L^{-1}; UQ = 102 mg L^{-1}) and Turbels (n = 820; 31 ± 62 mg L^{-1}; LQ = 12 mg L^{-1}; UQ = 74 mg L^{-1}), mineral permafrost soils that have experienced cryoturbation, had the lowest DOC concentrations. The median DOC concentrations found within the top 3 m of these soil classes represent <1% of the soil organic carbon stock found in the top 3 m of each soil class (Hugelius et al., 2014). DOC concentrations also differed within the thermal horizon of these different soil classes (chi-square = 91, df = 3, $p < 0.001$; Figure 2d). The highest DOC concentrations were found in permafrost free sites (n = 202; 57 ± 22 mg L^{-1}; LQ = 47 mg L^{-1}; UQ = 69 mg L^{-1}), which were largely Histosol soils (19%) or Histel soils (74%) that have experienced thermokarst formation. In areas where permafrost was present, DOC concentrations were highest in the active layer (n = 1,400; 45 ± 74 mg L^{-1}; LQ = 14 mg L^{-1}; UQ = 88 mg L^{-1}) and the permafrost lens (n = 729; 30 ± 113 mg L^{-1}; LQ = 10 mg L^{-1}; UQ = 123 mg L^{-1}).

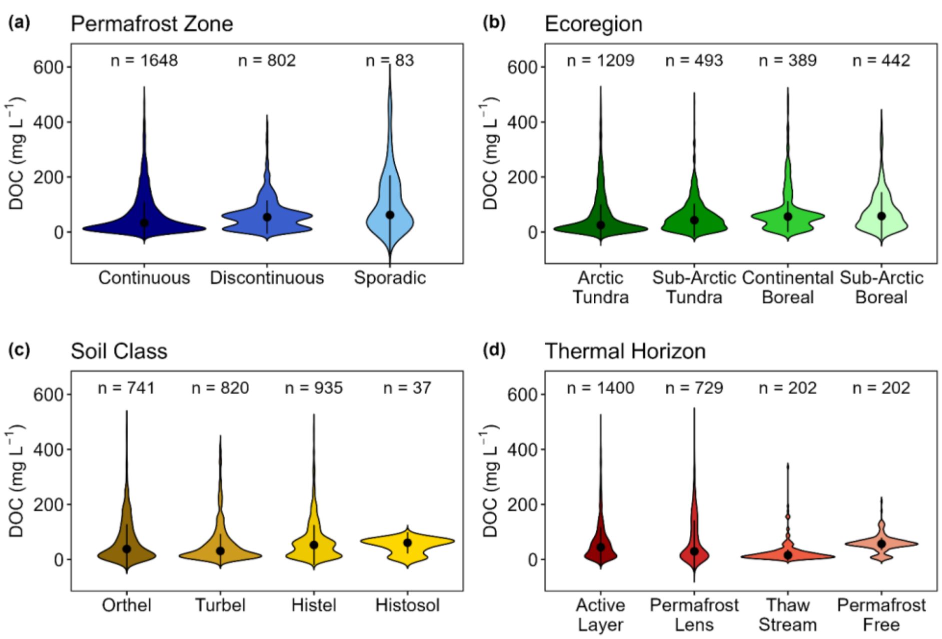

Figure 2. Violin plots of DOC concentrations (mg L^{-1}) found in the top 3 m across (a) permafrost zones, (b) ecoregions, (c) soil classes, and (d) thermal horizons. (a) Dark to light blue shading represents the permafrost zones Continuous, Discontinuous, and Sporadic, according to Brown et al., (1997). (b) Dark to light green shading represents the ecoregions Arctic Tundra, Sub-Arctic Tundra, Continental Boreal, and Sub-Arctic Boreal, according to Olson et al., (2001). (c) Dark to light yellow shading represents the soil classes Histosol, Histel, Orthel, and Turbel, according to the USDA Soil Taxonomy (USDA, 1999). ~~Histosols are organic rich, non-permafrost soil. Histels, Orthels, and Turbels are permafrost-affected soils (Gelisol order). Histels are organic rich, Orthels are non cryoturbated affected mineral soils, and Turbels are cryoturbated permafrost soils.~~ (d) Dark to light red shading represents the thermal horizons Active Layer, Permafrost Lens, Thaw Stream, and Permafrost Free. ~~Active layer represents the seasonally unfrozen soil layer above the permafrost layer. Permafrost Lens represents the permanently frozen (below 0°C) layer. Thaw Stream represents flowing surface waters following permafrost thaw. Permafrost Free represents areas that are not underlain by permafrost.~~ Black dots on each violin plot represents the median. Black vertical lines represent the interquartile range with the upper and lower limits representing the 75th and 25th percentiles, respectively. Either side of the black vertical line represents a kernel density estimation. This shape shows the distribution of the data, with wider areas representing a higher probability that samples within the database will have that DOC concentrations. The number of samples (n) found in each sub-category is found above each corresponding violin plot.

3.3 Trends in DOC concentrations across ecosystems

Similar to other categorical variables (i.e. permafrost zone, ecoregion, soil class, and thermal horizon data), DOC concentrations within each of the eight ecosystem types were found to be non-normally distributed, with median values skewed toward the lower end of the 0 – 500 mg L^{-1} range of concentrations (~~Figure A~~Figure S1). Permafrost bogs, upland tundra, and permafrost wetlands were the most represented in the database with regards to DOC concentrations (Table S1)~~, with a total of 685 concentrations from 38 studies and 679 concentrations from 22 studies, respectively~~. The majority of permafrost bog measurements came from studies with field sites within Canada (Figure 1; Table S1), as was the case for upland tundra and retrogressive thaw slump DOC concentration data. The majority of permafrost wetland sample locations were found in Russia, whereas the majority of the ~~399~~ 414 coastal tundra sampling locations were in the USA. The least represented ecosystem classes included the peatland ecosystem class, which is not strictly a permafrost ecosystem as the other are, and the Yedoma ecosystem class (145~~18~~ DOC concentrations from 9 studies, Table S1). DOC concentrations differed significantly across the eight ecosystem types (chi-square = 700, df = 7, *p*

< *0.001*; Figure 3). The highest DOC concentrations were found in coastal tundra (66 ± 116 mg L^{-1}~~; LQ = 24 mg L^{-1}; UQ = 140 mg L^{-1}~~) and permafrost bogs (63 ± 75 mg L^{-1}~~; LQ = 36 mg L^{-1}; UQ = 111 mg L^{-1}~~) ecosystems. The lowest DOC concentrations were found in permafrost wetlands (7 ± 20 mg L^{-1}~~; LQ = 6 mg L^{-1}; UQ = 26 mg L^{-1}~~) and Yedoma ecosystems (9 ± 18 mg L^{-1}~~; LQ = 2 mg L^{-1}; UQ = 20 mg L^{-1}~~), both of which had only slightly lower median DOC concentrations than retrogressive thaw slumps (15 ± 21 mg L^{-1}~~; LQ = 7 mg L^{-1}; UQ = 26 mg L^{-1}~~).

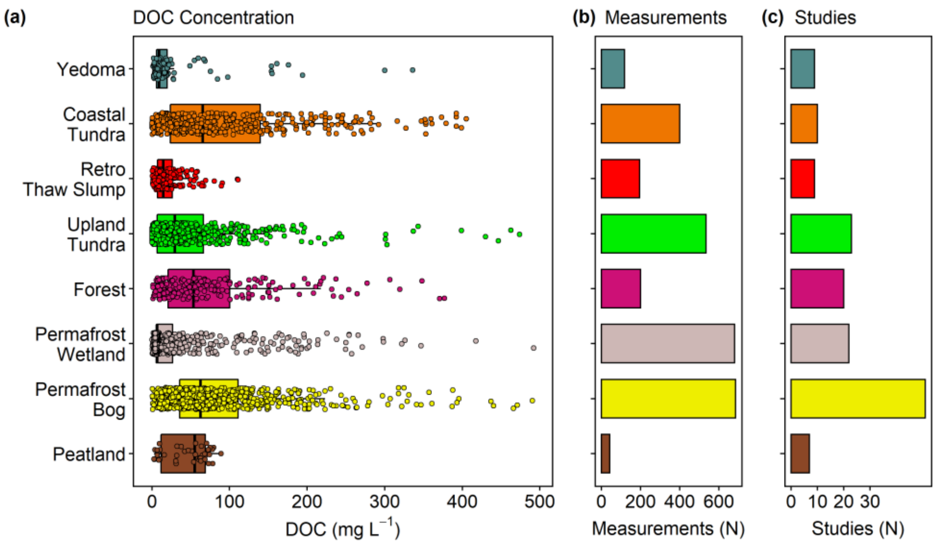

Figure 3. Boxplot and jitter plot of (a) DOC concentrations (mg L^{-1}), (b) the number of DOC measurements, and (c) number of studies including DOC measurements were taken from the top 3 m for each ecosystem type. Retro Thaw Slump = Retrogressive Thaw Slump. Boxes represents the interquartile range (25 – 75%), with median shown as black horizontal line. Whiskers extend to 1.5 times the interquartile range (distance between first and third quartile) in each direction. Jitter points represent the concentration of each individual DOC measurement, with random variation applied to each points location vertically in the plot, to avoid overplotting. Yedoma = dark teal. Coastal Tundra = orange. Retro Thaw Slump = red. Upland Tundra = green. Forest = purple. Permafrost Wetland = light pink. Permafrost bog = yellow. Peatland = brown.

When grouping all DOC concentrations by ecosystem types and differentiating between the active layer and permafrost lens thermal horizons, we found that DOC concentrations differed between the active layer and permafrost lens for all ecosystems (ANCOVA: $F_{(1, 1277)} = 49.8$, $p < 0.001$), except for permafrost bogs (chi-square = 0.37, df = 1, $p = 0.5$) and Yedoma (chi-square = 3.5, df = 1, $p = 0.06$) ecosystems (Figure 4). Within the permafrost lens thermal horizon, the highest DOC concentrations were found in coastal tundra (n = 103; 130 ± 119 mg L^{-1}~~; LQ = 60 mg L^{-1}; UQ = 179 mg L^{-1}~~) and permafrost bogs (n = 248; 78 ± 144 mg L^{-1}~~; LQ = 19 mg L^{-1}; UQ = 163 mg L^{-1}~~) sites, and lowest found in Yedoma sites (n = 91; 8 ± 10 mg L^{-1}~~; LQ = 6 mg L^{-1}; UQ = 16 mg L^{-1}~~). The highest active layer DOC concentrations were in permafrost bogs (n = 276; 64 ± 61 mg L^{-1}~~; LQ = 41 mg L^{-1}; UQ = 102 mg L^{-1}~~) and forest (n = 185; 57 ± 84 mg L^{-1}~~; LQ = 26 mg L^{-1}; UQ = 110 mg L^{-1}~~) sites, and lowest found in permafrost wetland sites (n = 274; 10 ± 42 mg L^{-1}~~; LQ = 5 mg L^{-1}; UQ = 47 mg L^{-1}~~).

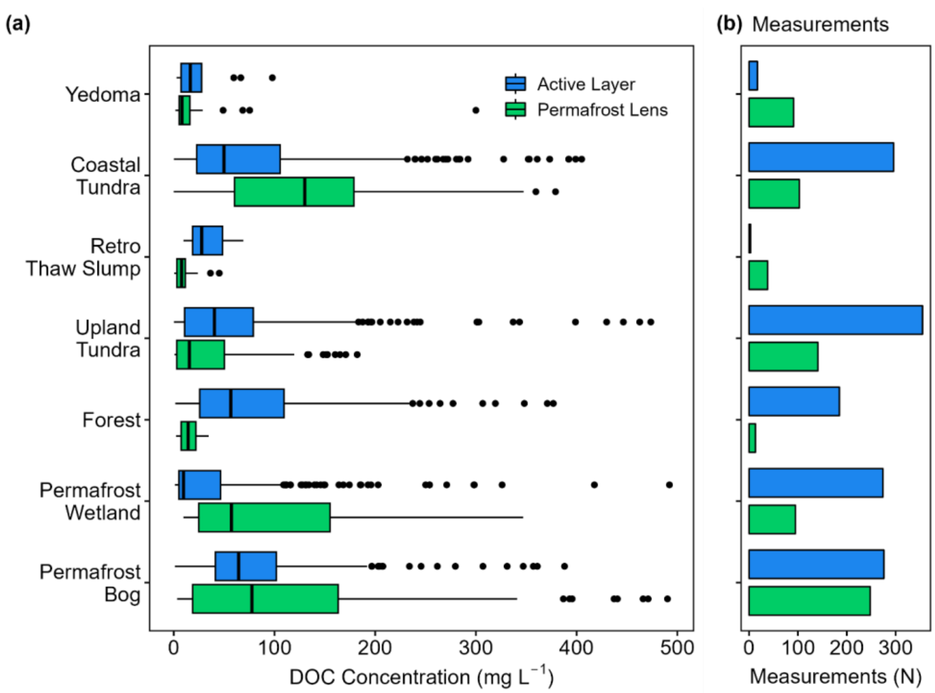

Figure 4 . Boxplot of (a) DOC concentrations (mg L^{-1}) and (b) ~~(b)~~ the number of DOC measurements in the Active Layer and Permafrost Lens thermal horizons of each ecosystem type. Only DOC concentrations from ecosystems with these thermal horizons present is used, thus no ~~peatland or~~ permafrost-free sites are included. Retro Thaw Slump = Retrogressive Thaw Slump. Boxes represents the interquartile range (25 – 75%), with median shown as black horizontal line. Whiskers extend to 1.5 times the interquartile range (distance between first and third quartile) in each direction. Blue boxplots represent DOC concentrations in the active layer. Green boxplots represent DOC concentrations in the permafrost lens.

3.4 Effect of extraction and analysis methods on DOC concentrations

We found that DOC concentrations differed between filter sizes (ANOVA: $F_{(4, 2339)} = 22.9$, $p < 0.001$) acro. The highest DOC median concentrations reported were filtered using 0.45 µm (53 ± 78 mg L^{-1}) and 0.22 µm (42 ± 54 mg L^{-1}) and lowest using 0.7 µm (17 ± 78 mg L^{-1}). The majority of DOC concentrations were determined using 0.45, 0.7, and 0.22 µm filter sizes. The trends observed in in DOC concentrations across study regions and ecosystems were also found when exploring these trends for the three main filter sizes used (Table S2, S3). Using 0.45 and 0.7 µm filter sizes, which represents 79% of all reported DOC concentrations, we find that DOC concentrations are generally higher in the discontinuous and sporadic permafrost zone, the two boreal ecoregions, Histel soils, and the active layer thermal horizons (Table S2). Similarly, the highest DOC concentrations using these two most common filter sizes were highest in permafrost bog and coastal tundra ecosystems (Table S3). Given these similarities when considering and not considering filter size, and the large variation in DOC concentrations within each filter size, we consider the effect of filter size on the trends observed in DOC concentrations across study regions and ecosystems reported above (Figure 2, 3) to be minor.

DOC concentrations were found to be significantly different between samples subject to the six broader groups of extraction method used (ANOVA: $F_{(5, 2518)} = 30.8$, $p < 0.001$), and between water based and soil (solid) based extraction methods (ANOVA: $F_{(1, 2524)} = 182.1$, $p < 0.001$). The trends observed in in DOC concentrations across study regions (Figure 2) and ecosystems (Figure 3) were also found when exploring study region and ecosystem trends for the three main DOC extraction methods used (Table S4, S5). We found that 93% of DOC concentrations were determined using the suction (42%), leach (37%), and grab (14%) extraction methods. Using these three most common approaches the highest DOC concentrations across study regions (Table S4) and ecosystems (Table S5) were found in the discontinuous and sporadic permafrost zone, the two boreal ecoregions, Histel soils, the active layer thermal horizons, and in permafrost bog and coastal tundra ecosystems.

The different methods of measuring DOC concentrations also produced significantly different DOC concentrations (ANOVA: $F_{(3, 2515)} = 36.2$, $p < 0.001$). The three most common accounted for 99% of all DOC concentrations and were combustion, persulphate, and photometric. Of these three combustion was the most common and used for 89% of DOC measurements. The persulphate and photometric methods were not used in all study regions (Table S6) and ecosystems (Table S7), thus comparison of all three methods is not complete. Trends in DOC measured using the combustion and persulphate method (Table S6, S7) were similar to those found across study regions (Figure 2) and ecosystems (Figure 3). This is unsurprising given that both of these methods account for 98% of all DOC concentrations.

We consider the effect of filter size, extraction method, and method of DOC measurement to be minor in determining trends in DOC concentrations across study regions and ecosystems. We find that trends in DOC concentrations across study regions and ecosystems are similar when you both consider and do not consider the methods used to determine those concentrations. Also, the variability observed in DOC concentrations for each study region and ecosystem remains high even when considering filter size, extraction method, and measurement method. Thus, each method or approach similarly impacts DOC concentrations from each study region and ecosystem, and cannot explain the DOC concentration variability observed within each. However, these different approaches did have an impact on DOC concentrations. In this study we did not focus on systematically testing the effect of filter sizes, extraction methods, or DOC measurement methods. Our goal was to assess the concentration and mobilization of DOC in terrestrial permafrost ecosystems across circumpolar regions and ecosystems. The assessment of methods is outside the scope of our study. Rather, we compare DOC concentrations collected from samples using a variety of these methods and suggest that future studies use this information to decide on methods to be consistent with compiled measurements, thus far.

3.54 Drivers of DOC concentrations

No continuous variables recorded in the dataset were available for all DOC concentration database entries, with no sites containing data for all continuous variables. This limited our ability to explore relationships between continuous environmental and ecological data and DOC concentrations across the permafrost region. To address drivers of DOC concentrations across the circumpolar permafrost region we used partial least squares regression (PLS) as it is tolerant to missing values. Multiple PLS regressions were run using various combinations of continuous and categorical data with similar model performance throughout. We chose the PLS to ~~predict~~ determine the drivers of DOC concentrations using environmental continuous variables and ecosystem type as this contained the lowest background correlation. The most parsimonious PLS regression extracted 9~~5~~ significant components, captured 79% variation of the predictor variables, and explained 37% of the variance in DOC concentrations in the dataset. The majority of the variance in DOC (35%) is explained along the first two axes of the model. The model was robust and not overfitted as model predictability was moderate ($Q^2 = 0.35$) and background correlation was low (0.006).

The PLS plot (Figure 5a) shows the correlation between DOC concentrations and selected environmental and ecological variables for the first two axes of the model. The two variables with the greatest positive and negative ~~effect on~~relationship with DOC concentrations were total dissolved nitrogen content (mg L^{-1}) and C:N ratios, respectively (Figure 5b). The positive relationship ~~between~~ of DOC ~~and~~ with total dissolved nitrogen and soil carbon content (SoilC), and negative relationship with the specific UV absorbance at 254 nm (SUVA), may be a result of ecosystem properties. The strong negative relationship with C:N ratios indicates that DOC concentrations decrease with increased decomposition. Other than higher soil carbon content (SoilC) in permafrost bogs, there was no clear or obvious observable trends in SoilC, TDN, C:N ratios, and SUVA across ecosystem types (~~Figure A~~Figure S3). The PLS demonstrates that ecosystem type strongly affects DOC concentrations, with DOC positively related with the highest ecosystems where the highest DOC concentrations are observed, permafrost bogs and coastal tundra, and negatively related to the lower DOC ecosystems, permafrost wetland and retrogressive thaw slumps (Figure 5). This negative relationship may be due to the higher latitudes these ecosystems are generally found at, which is supported by the negative relationship with DOC and the climate indicators mean annual temperature (MAAT) and mean annual precipitation (MAP). Additionally, it may be due to the high number of thermokarst affected sites found within these ecosystem classes, particularly retrogressive thaw slumps. There is a clear negative relationship between DOC concentrations and disturbed permafrost wetlands, retrogressive thaw slumps, and permafrost bogs.

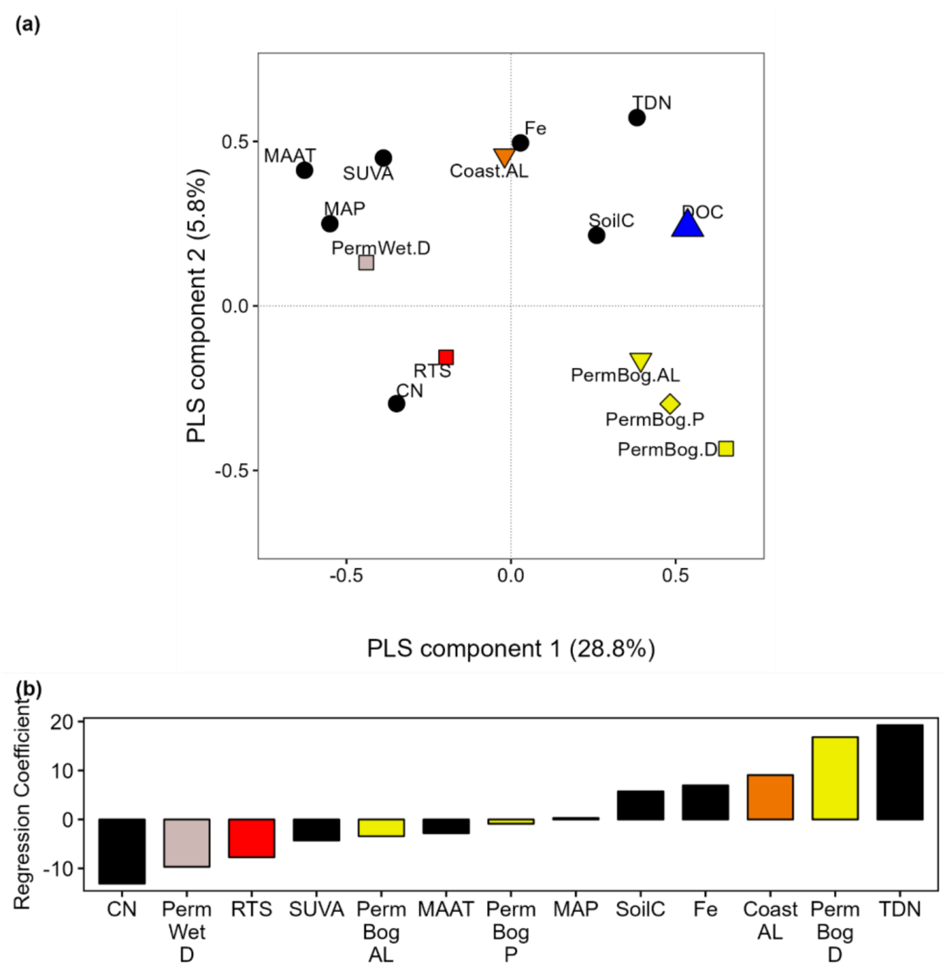

Figure 5. Partial least squares regression (PLS) (a) loadings plot explaining 37% of the variability observed in DOC concentrations. ~~PLS component axis 1 explains 28.8% of this~~

variability, whereas PLS component axis 2 explains 5.8%. The remaining axes explain the variability in DOC are not shown for clarity. (b) Bar plot of PLS regression coefficients showing the relative importance of each variable in predicting DOC concentrations. Regression coefficients on y-axis are normalized so their absolute sum is 100, with positive and negative values indicating the direction of the relationship. In the loadings plot squares depict ecosystem classes and the blue triangle represents DOC concentrations. Black circles in the (a) loadings plot and black bars in the (b) bar plot represent continuous environmental data that had at lest 20% coverage of DOC data,. All continuous data was log transformed, mean centered, and standardized. Continuous data variables are represented by the colour black. CN = carbon:nitrogen ratio. SUVA = the specific UV absorbance at 254 nm (L mg C^{-1} m^{-1}). MAP = mean annal precipitation (mm). MAAT = mean annual temperature. SoilC = carbon content of soil (g C kg^{-1}). TDN = total dissolved nitrogen (mg L^{-1}). Fe = dissolved iron ((mg L^{-1}). PermWet.D = disturbed permafrost wetland ecosystem class and is light pink (as in Figure 3) to represent this ecosystem class. RTS = retrogressive thaw slump ecosystem class and is red (as in Figure 3) to represent this ecosystem class. Coast.AL = active layer of coastal tundra ecosystem class and is orange (as in Figure 3) to represent this ecosystem class. PermBog.AL = active layer of permafrost bog ecosystem class and is yellow (as in Figure 3) to represent this ecosystem class. PermBog.P = permafrost lens of permafrost bog ecosystem class and is yellow (as in Figure 3) to represent this ecosystem class\. PermBog.D = disturbed permafrost bog ecosystem class and is yellow (as in Figure 3) to represent this ecosystem class.

3.65 Response and mobilization of DOC and BDOC to thermokarst formation

The highest DOC concentrations were found in pristine permafrost bog (n = 442; 75 ± 112 mg L^{-1}; LQ = 37 mg L^{-1}; UQ = 149 mg L^{-1}, n = 442) and coastal tundra ecosystems (n = 427; 72 ± 126 mg L^{-1}; LQ = 25 mg L^{-1}; UQ = 151 mg L^{-1} n = 427; Figure 6a). No thermokarst affected coastal tundra ecosystems were recorded within the dataset. Whereas, in permafrost bogs DOC concentrations were found to differ across different thermokarst disturbances (ANOVA: $F_{(3, 720)} = 23.04$, $p < 0.001$), with the lowest found in thermokarst wetlands (n = 16; 10 ± 21 mg L^{-1}; LQ = 9 mg L^{-1}; UQ = 30 mg L^{-1}, n = 16). DOC concentrations were also found to differ between thermokarst affected and pristine sites in upland tundra ecosystems (ANOVA: $F_{(3, 539)} = 5.91$, $p < 0.001$). The highest DOC concentrations in upland tundra ecosystems were found in sites that had experienced active layer thickening (n = 142; 53 ± 39 mg L^{-1}; LQ = 41 mg L^{-1}; UQ = 80 mg L^{-1}, n = 142), whereas the lowest were found in sites that had experienced active layer detachment (n = 6; 4 ± 2 mg L^{-1}; LQ = 3 mg L^{-1}; UQ = 5 mg L^{-1}, n = 6). Pristine sites had the highest DOC concentrations in both Yedoma (n = 114; 11 ± 15 mg L^{-1}; LQ = 6 mg L^{-1}; UQ = 21 mg L^{-1}, n = 114) and forest (n = 189; 49 ± 64 mg L^{-1}; LQ = 22 mg L^{-1}; UQ = 86 mg L^{-1}, n = 189) ecosystems. However, in permafrost wetland ecosystems pristine sites had the lowest DOC concentrations (n = 766; 7 ± 51 mg L^{-1}; LQ = 6 mg L^{-1}; UQ = 57 mg L^{-1}, n = 766) with sites that were affected by both thermokarst wetland formation (n = 17; 21 ± 26 mg L^{-1}~~; LQ = 11 mg L^{-1}; UQ = 37 mg L^{-1}, n = 17~~) and active layer thickening (n = 12; 41 ± 13 mg L^{-1}~~; LQ = 34 mg L^{-1}; UQ = 47 mg L^{-1}, n = 12~~) having higher DOC concentrations.

Our database contained limited data regarding BDOC (n = 146), thus BDOC results across ecosystems should be interpreted with caution. Due to limited data we have combined BDOC over all incubation lengths when assessing BDOC between pristine and thermokarst sites (Figure 6). BDOC was found to differ between thermokarst disturbances within ecosystem types in only Yedoma (ANOVA: $F_{(2, 27)} = 23.09$, $p < 0.001$) and permafrost wetland (ANOVA: $F_{(1, 10)} = 15.87$, $p < 0.001$) ecosystems. The highest BDOC was found in both of these ecosystem types also, with 54% (n = 5) in pristine Yedoma sites and 49% (n = 8) in thermokarst wetland affected permafrost wetland sites (Figure 6b), with the latter exhibiting the highest BDOC across all permafrost affected sites followed by thaw slumps (18%, n = 11) in Yedoma ecosystems and active layer thickening (40%, n = 1) in upland tundra sites. The lowest median BDOC of 4% were seen in thermokarst bogs (n = 5) and active layer thickening (n = 3) affected sites, with pristine sites experiencing BDOC of 9% (n = 15). However, not all ecosystem types in the database had BDOC data for both pristine and disturbance sites. For example, only pristine sites data was available for forests, whereas there was no pristine site data available for upland tundra sites. No BDOC data was available for coastal tundra sites.

All ecosystem types that had BDOC data, reported BDOC observed following 40 – 90 incubation days, and this also corresponded to the highest BDOC values for each ecosystem type (~~Figure A~~Figure S4). When comparing the greatest BDOC observed within this incubation length window, we found that values varied across ecosystem type (ANOVA: $F_{(5, 131)} = 14.6$, $p < 0.001$). The highest loss rates were observed in Yedoma and permafrost wetland ecosystems, whereas the lowest we observed in organic rich forest and permafrost bog ecosystems (~~Figure A~~Figure S4). Forest (ANOVA: $F_{(1, 16)} = 2.31$, $p = 0.15$) and permafrost bog (ANOVA: $F_{(3, 24)} = 2.49$, $p = 0.09$) BDOC did not differ over incubation length, whereas Yedoma (ANOVA: $F_{(4, 25)} = 24.92$, $p < 0.001$) and permafrost wetland (ANOVA: $F_{(1, 10)} = 15.87$, $p < 0.01$) did differ over time, with their max occurring during this 40 – 90-day incubation length. This suggests that when incubated for the same number of days, we would expect greater BDOC in Yedoma and permafrost wetland ecosystems. Note, for this analysis BDOC values from all thermokarst and non-thermokarst affected sites within an ecosystem type were included. Given the limited BDOC data available we have compared BDOC across ecosystems in two ways. The first is using data from all measurement days to assess BDOC across pristine and disturbed ecosystems (Figure 6b). The second is assessing max BDOC within each ecosystem type, which includes pristine and disturbed sites (Figure S4). Using both approaches we find that the highest BDOC is observed in high-latitude Yedoma and permafrost wetland sites.

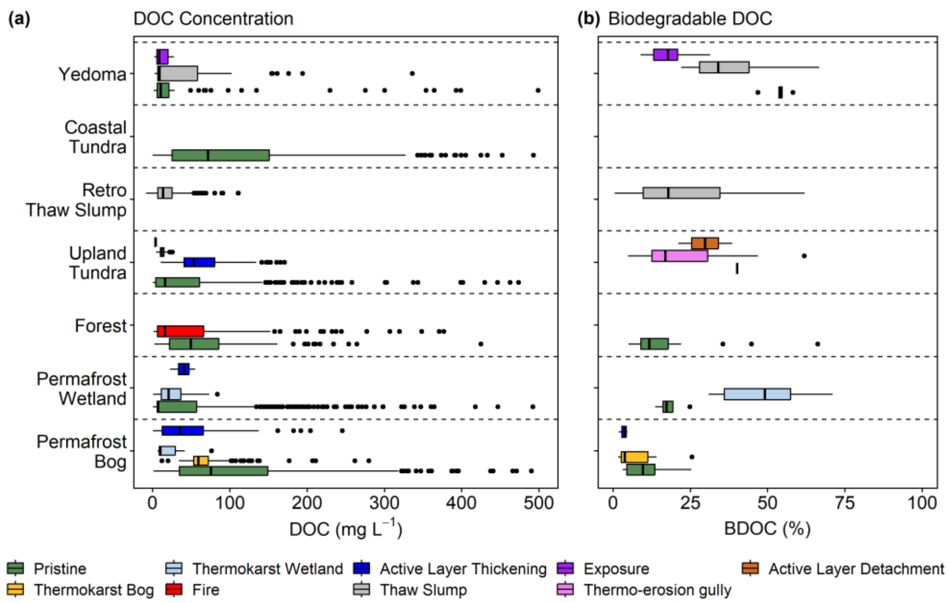

Figure 6. DOC concentrations (mg L^{-1}) and biodegradable DOC (BDOC; %) from the top 3 m following disturbance including data from both field based and incubation studies. (a) DOC concentrations from each ecosystem type following disturbance where data was available. (b) Biodegradable DOC (BDOC) from each ecosystem type following disturbance where data was available. BDOC loss was determined following 3 – 304 days of incubation. Data from different incubation lengths was combined due to low sample size. Retro Thaw Slump = Retrogressive Thaw Slump. Boxes represents the interquartile range (25 – 75%), with median shown as black horizontal line. Whiskers extend to 1.5 times the interquartile range (distance between first and third quartile) in each direction, with outlier data plotted individually as black dots. Note colours associated with boxplots in this figure are only relevant for this figure.

Response ratios comparing the change in DOC concentrations between pristine and thermokarst affected sites were calculated from our dataset from 108 studies using Eq. 1 (Figure 7). Only 17 studies provided data for both pristine and thermokarst affected ecosystems, with 87 papers providing DOC concentrations from pristine and 34 from thermokarst affected sites. When considering all ecosystems together we found that response ratios were negative, suggesting that DOC concentrations were higher in thermokarst affected sites compared to pristine sites (Figure 7). These negative response ratios were most evident in permafrost bogs, where they found throughout the entire column and individual thermal horizons. The greatest increase in DOC concentrations following thermokarst was seen when comparing DOC concentrations in the permafrost lens of permafrost bogs, and to a lesser extent permafrost wetlands (Figure 7). Only in Yedoma ecosystems did we see positive response ratios throughout the entire profile, suggesting a decrease in DOC concentrations following thermokarst formation in Yedoma sites. This was also seen for DOC concentrations within the permafrost lens of upland tundra sites, which include DOC concentrations from retrogressive thaw slumps and thermo-erosion gullies in their thermokarst affected sites. The large confidence intervals for some response ratios suggests high variability in the response of DOC concentrations to thermokarst formation.

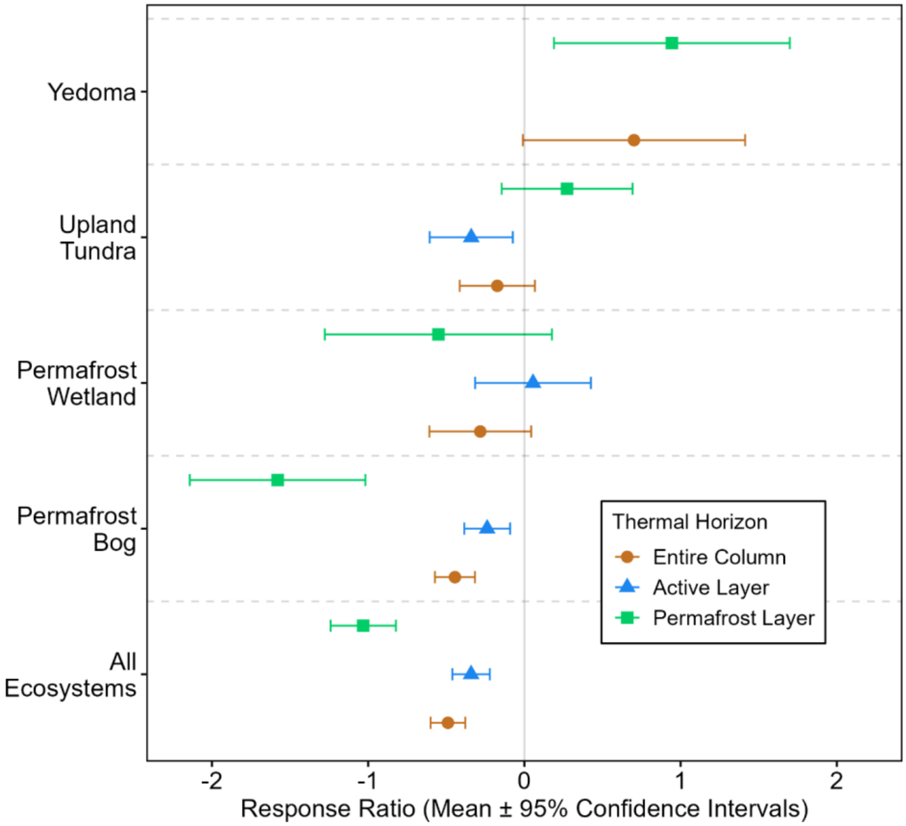

Figure 7. Response ratios of DOC concentrations from the top 3 m following thermokarst formation (calculated using Eq. 1). Response ratio means allow for relative comparison of changes in DOC following thermokarst formation between different ecosystem types. Negative values indicate lower DOC concentrations found in pristine ecosystems, whereas positive value indicates a decrease in DOC concentrations following thermokarst. Studies reporting DOC concentrations from Exposures, Retrogressive Thaw Slumps, and Thermo-Erosion Gullies from sites within the continuous permafrost zone were combined into the Upland Tundra ecosystem category. This did not include DOC concentrations from studies within the Yedoma permafrost domain (Strauss et al., 2021). Blue line represent DOC concentrations in the active layer, as per Figure 4. Green lines represent DOC concentrations in the permafrost lens, as per Figure 4.

Brown lines represent DOC concentrations from the entire column (i.e., both active layer and permafrost lens).

4. Discussion

In this systematic review, we evaluated patterns of DOC concentrations in the top 3 m of soil in terrestrial ecosystems across the northern circumpolar permafrost region based on results from 111 studies and 2,845 DOC measurements. We focused on comparing concentrations of DOC in soils across various geographical regions, ecological conditions, and disturbance types. Our synthesis shows that median DOC concentrations across ecosystems range from 9 – 61 mg L^{-1}, which represents similar albeit slightly higher DOC concentrations when compared to the median DOC concentrations found in top soils of other land cover groups below 50°N (25 mg L^{-1}; Langeveld et al., 2020), globally distributed lakes (6 mg L^{-1}; Sobek et al., 2007), and lakes across the permafrost region (11 mg L^{-1}; Stolpmann et al., 2021). In general, we show that organic soils have higher DOC concentrations than mineral soils, and that DOC concentrations are positively related to total dissolved nitrogen concentrations and negatively to C:N ratios, which corroborate previous findings of factors correlating with DOC concentrations (Aitkenhead & McDowell, 2000; Lajtha et al., 2005). Overall, we found that properties associated with ecosystem type are the main constraint on DOC concentrations. Furthermore, disturbance through permafrost thaw has little impact on measured DOC concentrations, however this may be due to the loss of biologically reactive DOC or the loss of an initially larger pulse of DOC having been previously mobilised prior to the timing of sampling.

4.1 Environmental factors influencing DOC

Our database confirmed our first hypothesis that the highest DOC concentrations would be found in organic rich soils. Previous synthesis efforts estimating global distributions of terrestrial DOC concentrations have presented similar findings (Guo et al., 2020; Langeveld et al., 2020). Both of these previous studies also show that some of the highest terrestrial DOC concentrations are found within the northern circumpolar permafrost region, highlighting that these high DOC concentrations found in organic rich permafrost soils are of global significance. Concentrations of DOC in the top 3 m of soils closely mirrored stocks of SOC across the circumpolar permafrost region (Hugelius et al., 2014). Organic rich Histosol and Histel soils contain the greatest SOC per km^2, followed by Turbels and Orthels (Hugelius et al., 2014). The leaching of organic C from soils act as a major source of DOC (Kalbitz et al., 2000; Marschner & Bredow, 2002), thus it is not surprising that we find, the highest as was seen in DOC concentrations in the across these soil types with the greatest quantities of SOC (Figure 2a). While the highest DOC concentrations are found within organic rich soils, the amount of C found as DOC represent a small amount of the total SOC pool. Using the current best estimates of Histel SOC stocks (Hugelius et al., 2020), the DOC pool represents <1% of the total C stock in permafrost-affected peatlands as has been shown for both permafrost and global soils (Guo et al., 2020; Prokushkin et al., 2008).

4.2 Thermal horizons

In many ecosystems, DOC concentrations are greatest in the active layer nearer the surface (Figure 4). This trend has also been observed in the vertical distribution of DOC across global soils, with 50% of the DOC pool found in the top 0 – 30 cm (Guo et al., 2020). The production of DOC is associated with soil microbial activity (Guggenberger & Zech, 1993) and plant inputs (Moore & Dalva, 2001), and the microbial production of DOC via input of labile substrates has been shown to decrease with depth in permafrost (Hultman et al., 2015; Monteux et al., 2018; Wild et al., 2016). Furthermore, the organic matter content decreases and mineral content increases with depth, this depth trend and decrease in DOC with depth is particularly evident between the active layer and permafrost lens in forest ecosystems (Figure 4a). While permafrost and non-permafrost bogs do also see a shift in microbial community with depth (Heffernan & Cavaco et al., 2022; Lamit et al., 2021), the movement of modern, surface derived DOC down into deeper layers has also been observed (Chanton et al., 2008; Estop-Aragonés et al., 2018). These, combined with the large, frozen SOC stores found at depth (Hugelius et al., 2020) and hydrological isolation (Quinton, Hayashi, & Chasmer, 2011), results in a DOC pool that remains relatively similar across thermal horizons in permafrost bogs (Figure 4b). Intriguingly, in both coastal tundra and permafrost wetland ecosystems, DOC concentrations were found to be higher in the permafrost lens than in the active layer. This suggests that DOC within the active layer of these ecosystems experienced some degree of mobilization, either via export to the aquatic network or enhanced decomposition within soils. The higher DOC concentrations found within the permafrost lens of these ecosystems may represent a vulnerable DOC pool to enhanced mineralization following permafrost thaw (Figure 6).

Commented [LH3]: Incorporate this section into the section below and remove the 2nd hypohtsis in intro

This section is not that interested but oculd be sed to supplemnt the next

Eg forests are high only becaise of upper organics in acitve layer, whereas the rest are low beciase they are mneral rich

Permaforst bogs are high becaise they are high everywhere

Coast is high because of high frozen stores - potenmtally vulberable!

Commented [LH4]: This should be in the intro

4.23 Variation in DOC amongst across permafrost zones and ecoregionsecosystems

Permafrost soils are estimated to store 1,035 ± 150 Pg C globally within the top 0-3 m (Hugelius et al., 2014), with the highest storage of SOC found in the organic rich Histosols and Histels. While persistent low temperatures are the main common factor which has led to the accumulation of such high SOC amongst all permafrost soils, environmental factors associated with the different ecosystem types are the main driving factors in differences amongst DOC concentrations. The source of the permafrost DOC pool is from recent plant leachate inputs, or from the decomposition and solubilization of SOC. Thus, the molecular composition of the DOC pool is derived from a mixture of current and historical vegetation inputs. There are clear current and historical shifts in dominant vegetation seen in the permafrost region from the south (boreal) to north (arctic tundra), as well as across ecosystem types (upland forest, upland tundra, arctic and boreal wetland). However, the majority of vegetation and its leachates found in the permafrost region are generally found to produce relatively stable DOC (in terms of BDOC) consisting of lignin-derived compounds, highly aromatic polyphenolic compounds, and low molecular weight organic acids (Chen et al., 2018; Drake et al., 2015; Ewing et al., 2015; Selvam et al., 2017). While differences in the stability of different DOC source end-members have been shown (MacDonald et al., 2021), differences in redox conditions are likely a major driver in differences in the accumulation and mineralization of DOC across permafrost ecosystem types (Mohammed et al., 2022).

Similar to their globally significant stores of SOC (Hugelius et al., 2020), Tthe accumulation of high DOC concentrations found we show in peatlands, permafrost bogs, and permafrost wetlands (Figure 3), is a result of the prevalence of cold and anoxic conditions throughout the Holocene (Blodau, 2002). This leads to a reduction in microbial decomposition, and the accumulation of both thea large SOC (Hugelius et al., 2020) and DOC pool. Our results suggest that the pristine permafrost bog and permafrost wetland DOC pool is relatively stable following permafrost thaw (Figure 6, 7a). The lower DOC pool found in the active layer of permafrost wetland (Figure 4a) may represent a potentially labile DOC pool (Figure 7a), but this is likely due to fresh, plant derived inputs rather than the exposure and mineralization of previously frozen organic matter (Figure 7a). Peatland vegetation, in particular *Sphagnum* mosses, produces litter that has anti-microbial properties and is decay resistant (Hamard et al., 2019; Limpens,

Commented [LH5]: For this section combine the first two paragraphs. They don't contain a great deal of information other than waffle, maybe some could be used in the introduction instead

Rather, start with the claim that we find that the higest doc is found in areas where we find the highest soc. This follwos latitudinal trend whereby the highest concentrations are found near the sotuh in organic rich soils. Then go on to discuss this

Then have a paragraph just on coastal site, beef up the pragrap[h already there

The final paragraph could be renived too or incorporated to the previous (eg forests into laittudianl story and organnic rich soils, or perm wet into that story)

Commented [LH6]: Condense this and send to the intro

Bohlin, & Nilsson, 2017), limiting the amount of SOC that is degraded and assimilated into the DOC pool (Tfaily et al., 2013). This is further enhanced by the build-up of decomposition end products and the thermodynamic constraint on decay observed in anoxic soils (Beer et al., 2008). Permafrost has been continuously present in peatlands across the northern circumpolar permafrost region for the past 6,000 years, with the greatest rates of permafrost formation occurring within the past 3,000 years (Treat & Jones, 2018). Thus, a large proportion of the organic matter found peatlands and wetlands in this region were present prior to permafrost aggradation (i.e., permafrost formation), which indicates that permafrost formed epigenetically in these areas. Permafrost aggradation impacts soil biogeochemical properties, leading to potentially less decomposed organic matter with higher C/N ratios than non-permafrost equivalent soils, particularly in permafrost wetlands (Treat et al., 2016). This can lead to the build-up of high DOC concentrations that are vulnerable to potential mobilization following thermokarst. Decomposition in epigenetic permafrost bogs following thermokarst has been shown to be relatively slow (Heffernan et al., 2020; Manies et al., 2021), which further supports our finding (Figure 6) that the large DOC pool found in these systems in relatively stable following permafrost thaw. ~~The permafrost wetland DOC pool that accumulates following thermokarst may represent a potentially labile DOC pool (Figure 7a), but this is likely due to fresh, plant derived inputs rather than the exposure and mineralization of previously frozen organic matter (Figure 7a).~~

Coastal tundra ~~and forest~~ ecosystems had similarly high DOC concentrations to those found in permafrost bogs (Figure 3a). Coastal tundra ~~and forest~~ ecosystems represented the highest concentrations of DOC in mineral permafrost soils, with the highest concentrations found in the permafrost lens (Figure 4a). ~~Concentrations of coastal permafrost DOC were significantly lower in the active layer compared to within the permafrost lens (Figure 4a).~~ This is contrary to findings that deeper coastal permafrost consists of low organic matter Pleistocene marine sediments (Bristol et al., 2021) and the proximity of the active layer to vegetation inputs, although this productivity and inputs are vulnerable to projected climatic warming and regional “browning” and “greening” (Lara et al., 2018). Recent work has shown that DOC in the active layer within the coastal permafrost is more biodegradable that OC in the permafrost lens (Speetjens et al., 2022) and a substantial proportion of organic carbon derived from thawing coastal permafrost is vulnerable to mineralization upon thawing, particularly when exposed to sea water (~~George~~ Tanski et al., 2021). Export of terrestrial coastal permafrost DOC directly into the Arctic Ocean can significantly influence marine biogeochemical cycles and food webs within the Arctic ocean (Bruhn et al., 2021). Arctic coasts are eroding at rates of up to 25 m yr^{-1} (Fritz, Vonk, & Lantuit, 2017) and exporting large quantities of terrestrial organic matter export directly to the ocean that is rapidly mineralized (Tanski et al., 2019). Enhanced DOC export from these coastal tundra ecosystems may disrupt aquatic food webs through altering nutrient and light supply, as has been shown for Swedish coastal systems (Peacock et al., 2022). These coastal tundra sites represent a large DOC pool that is highly vulnerable to enhanced mobilization and deserve further attention.

We found that DOC concentrations increased along a clear latitudinal gradient, from north to south, in ~~The~~ the remaining ecosystems characterised by mineral soils with an upper organic layer, i.e., f~~F~~orests, u~~U~~pland t~~T~~undra, and ~~Yedoma~~Yedoma. ~~, followed a clear latitudinal climate gradient of increasing DOC concentrations from north to south.~~ In forest ecosystems, the upper organic layer, and the impact of soil temperature, moisture, and pH on SOC found there, strongly influences the production, concentration, and composition of DOC (Neff & Hooper, 2002; Wickland et al., 2007). Furthermore, the sorption of DOC to charcoal (Guggenberger et al., 2008), and high lignin and phenolic input from vegetation (O'Donnell et al., 2016) produce a difficult to degrade DOC pool, leading to the accumulation of the large DOC pool in the active layer (Figure 4a) this ecosystem type. This trend with depth has also been observed in the vertical distribution of DOC across global soils, with 50% of the DOC pool found in the top 0 – 30 cm (Guo et al., 2020). While not included in the most parsimonious PLS model (Figure 5), Yedoma and u~~U~~pland t~~T~~undra ecosystems were found to negatively correlate with DOC concentrations (~~Figure A~~Figure S5). The greatest proportions of OC and nutrients used for DOC production in these ecosystems are found in shallow organic layers (Semenchuk et al., 2015; Wild et al., 2013) ~~in these ecosystems~~. Beneath the upper organic horizons in these mineral soils processes such as sorption of DOC to minerals and the formation of Fe-DOC or Al-DOC complexes may remove DOC from the dissolved pool (Kawahigashi et al., 2006) and mechanically protect it from mobilization (Gentsch et al., 2015). The majority of vegetation and its leachates found in the permafrost region produce relatively stable DOC consisting of lignin-

Commented [LH7]: Add in a russian reference here derived compounds, highly aromatic polyphenolic compounds, and low molecular weight organic acids (Chen et al., 2018; Drake et al., 2015; Ewing et al., 2015; Selvam et al., 2017). In forest ecosystems, large amounts of SOC have accumulated in surface organic layers through increased vegetative inputs due to warmer and longer growing seasons. This organic layer depth, and the impact of soil temperature, moisture, and pH on SOC found there, strongly influences the production, concentration, and composition of DOC (Neff & Hooper, 2002; Wickland et al., 2007). Furthermore, the sorption of DOC to charcoal (Guggenberger et al., 2008), and high lignin and phenolic input from vegetation (O'Donnell et al., 2016) produce a difficult to degrade DOC pool, leading to the accumulation of the large DOC pool in this ecosystem type. While differences in the stability of different DOC source end-members have been shown (MacDonald et al., 2021), differences in redox conditions are likely a major driver in differences in the accumulation and mineralization of DOC across permafrost ecosystem types (Mohammed et al., 2022).

Commented [LH8]: Condense this and send to the intro

Field Code Changed

Commented [LH9]: Make this fit better, butr use it to round out this section stating that redox is proibably th emost important ecosystem factor infleunceing DOC (direct and indirect)

4.34 Vulnerability of DOC to enhanced mobilization following thermokarst

We define DOC mobilization as DOC lost from an ecosystem either via export or degradation. Our second hypothesis that permafrost thaw would lead to enhanced mobilization of DOC cannot be fully supported by the findings from this database. Using our chosen systematic approach and focusing on data from terrestrial ecosystems, our database was limited to 3 studies which represented <1% of the DOC concentration data. Several previous studies have detailed the export of DOC in Arctic inland waters, see Table 2 in Ma et al., (2019). These studies were excluded using our systematic approach (Table 1 and 2) as they do not directly measure DOC export from a terrestrial ecosystem, rather they determine the quantity of terrestrial derived DOC found in inland waters. This is a key distinction, as by not quantifying the export rates for terrestrial ecosystems the net ecosystem carbon balance and vulnerability to enhanced export may not be assessed., that have been excluded using this approach. We acknowledge the limitation in our approach regarding the inclusion of DOC export data. Thus, this database cannot be used to determine how permafrost thaw will influence DOC export from terrestrial ecosystems within the northern circumpolar permafrost region. However, we identify this lack of export data from terrestrial permafrost ecosystems as a key knowledge gap in our current understanding of the permafrost carbon pool. Currently, Arctic rivers are estimated to export 25

– 36 Tg DOC year^{-1} (Amon et al., 2012; Holmes et al., 2012), with this being dominated by modern carbon sources (Estop-Aragonés et al., 2020), most likely derived from the top 1 m of terrestrial ecosystems. Using current best estimates of the areal extent and soil organic carbon stores in the top 1 m of Histosols, Histels, Orthels and Turbels (Hugelius et al., 2014), and if we assume that the DOC pool represents ~1% of the SOC pool, we estimate that <1% of the current DOC pool found in the top 1 m of Histosols, Histels, Orthels and Turbels is exported annually to Arctic rivers. Quantifying the proportion of these DOC pools annually lost, and particularly the proportions lost in headwater streams while being exported to Arctic rivers, is vital to assess the importance of the mobilization of the terrestrial permafrost DOC pool.

Our calculated response ratios (Figure 7) for all ecosystems, indicating the difference in DOC concentrations between pristine and permafrost thaw affected sites, partly supports of our second hypothesis that disturbance would lead to increased export and biodegradability of DOC. The increase in DOC following thaw observed in permafrost bogs is likely due to increased inputs due to increased runoff and shifts in vegetation following permafrost thaw (Burd, Estop-Aragonés, Tank, & Olefeldt, 2020), enhanced release of DOC (Loiko et al., 2017), a relatively stable soil organic carbon pool at depth due to several millennia of microbial processing (Manies et al., 2021), the prevalence of anoxic conditions, and the potential hydrological isolation of thermokarst bogs (Quinton, Hayashi, & Pietroniro, 2003). While not included in our analysis, DOC found near the surface of the permafrost lens in forest ecosystems has been shown to be more biodegradable than DOC found in the active layer (Wickland et al., 2018), and may represent a decrease in DOC following thermokarst not captured here. Our findings of limited mobilization of permafrost bog DOC upon thawing are supported by the findings that the ^{14}C signature of DOC in Arctic rivers is dominated by modern sources (Estop-Aragonés et al., 2020). However, individual studies have determined that thawing may release a large pool of permafrost peatland DOC into aquatic networks (Lim et al., 2021). ~~However, w~~We do see a reduction in DOC concentrations in thermokarst affected sites at the higher latitude Yedoma, upland tundra, and permafrost wetland ecosystems. This reduction in DOC concentrations in these ecosystems may be due to the greater biodegradability and lability of the DOC found there (Figure 6b), supporting our third hypothesis that the most biodegradable DOC would be found in higher latitude ecosystems. Permafrost DOC in higher latitude ecosystems, particularly Yedoma ecosystems, is characterised by syngenetic permafrost aggradation which have not undergone centuries to millennia of soil formation and microbial processes, have been shown contain a greater proportion of low oxygen, aliphatic compounds and labile substrates (Ewing et al., 2015b; MacDonald et al., 2021). This leads to a greater biolability and rapid mineralization of DOC (Vonk et al., 2015), potentially causing the reduction in DOC concentrations observed following thaw. If this hypothesis is to be found true across all high latitude ecosystems with further data, it further highlights the vulnerability of the large DOC pool found in coastal tundra ecosystems.

In this study, we focus on the dissolved fraction of the OC pool, however the particulate fraction should also be considered when discussing the mobilization of terrestrial OC in permafrost landscapes. In boreal freshwater networks, particulate organic carbon (POC) represents a small but highly labile fraction of terrestrially derived OC exported to the fluvial network (Attermeyer et al., 2018). The degradation of permafrost derived POC is much slower than that of POC in the boreal freshwater network and POC derived from younger sources along the riverbank (Shakil, Tank, Kokelj, Vonk, & Zolkos, 2020). The DOC pool in Arctic freshwaters in dominated by modern terrestrial sources (Estop-Aragonés et al., 2020), whereas the POC pool has been shown to be dominated by older sources in both permafrost peatland dominated areas (Wild et al., 2019), following the formation of retrogressive thaw slumps (Keskitalo et al., 2021), and in thermokarst affected periglacial streams (Bröder et al., 2022). This older POC has been shown to accumulate following export due to low lability and degradation and mineral association, which suggests that upon thermokarst formation, previously frozen OC exported in the particulate phase is not readily consumed by microbes and that permafrost derived DOC is the more labile fraction of exported terrestrial OC.

4.4~~5~~ Future considerations for study design

Determining the fate of mobilized terrestrial DOC in both permafrost thaw affected, and pristine sites should be prioritized in future studies to constrain current estimates of the permafrost C climate feedback. There are large spatial gaps in the database, particularly in areas with large stock of permafrost C such as the Hudson Bay Lowlands and Mackenzie River Basin, both in Canada and two of the three largest deposits of permafrost peatland C in the circumpolar permafrost region (Olefeldt et al., 2021). Similarly, coastal tundra sites, which along with permafrost bog represent the ecosystems with the highest DOC concentrations, were sampled only along the northern shoreline of Alaska and the Yukon (USA and Canada, respectively; Table S1). From our analysis of this database, we determine that DOC mobilization is poorly understood for terrestrial permafrost ecosystems. To address this, the two main needs of future studies are 1) more direct estimates of DOC fluxes and export from terrestrial ecosystems into aquatic ecosystems, and 2) more DOC degradation (BDOC) and mineralization studies. Our results suggest that the high concentrations of DOC in permafrost bogs remains relatively stable upon thermokarst formation, although individual studies do indicate that thawing peat may provide a reactive source of DOC (Panneer Selvam et al., 2017). Whereas the The database did not include any studies that reported on the mineralization of DOC from coastal tundra sites, thus we are unable to comment on the stability of the high DOC concentrations found in this ecosystem type. Further sampling and assessing the mineralization of DOC is required to characterize the potential pool of vulnerable DOC in areas with high DOC concentrations. Overall, our database and systematic approach only included 5 studies (Olefeldt & Roulet, 2012, 2014; Olefeldt et al., 2012; Prokushkin et al., 2006; Prokushkin et al., 2005) that explicitly reported rates of DOC discharge, export, or fluxes from terrestrial ecosystems into the fluvial network. Given the importance of terrestrial DOC as a source for CO_2 production within the aquatic network (Weyhenmeyer et al., 2012), and the findings that previously frozen DOC is being exported to the freshwater network (Estop-Aragones et al., 2020), improved estimates of the quantity of terrestrial DOC being exported is essential to determine the potential aquatic greenhouse gas fluxes derived from the mineralization of terrigenous organic matter. To improve current estimates of the permafrost C feedback further studies are needed to determine how much DOC is laterally exported from terrestrial ecosystems, and the mineralization potential of this DOC along the terrestrial-freshwater-aquatic continuum.

Lastly, we suggest that future studies should consider a standardization of methods and approached used to determine DOC concentrations for better comparison across studies. In constructing this database we identified three3 different filter sizes, eleven11 different extraction procedures, and four4 different measurement methods. The most common filter size used was 0.45 µm and this has previously been described as the cut off to separate DOC from colloid materials (Thurman 1985; Bolan et al., 1999). In extracting DOC concentrations from soils the mostly commonly used approach (70% of all soil samples) was via soil leaching with no chemical treatment of the soils, although some added filtered water to promote leaching. From the seven approaches identified to extract water samples from terrestrial sites in determining DOC, 48% of samples were collected using a variety of suction devices and 46% done via grab samples. Of the four DOC measurements methods the most common approach was by combustion, with 90% of all DOC concentrations measured using this approach. As such, in order to continue measuring DOC concentrations in terrestrial permafrost ecosystems using the most consistent approach we suggest using 0.45 µm filters, extracting pore water via some type of sucking device or soils via leaching, and using a combustion based method to determine DOC concentrations

Data availability

All data will be made freely and publicly available on an online repository prior to publication

Author contributions

LH, DK, and LT designed and planned the systematic review approach; LH built the database. LH and DK analyzed the data; LH wrote the manuscript draft; DK and LT edited and reviewed the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We thank Konstantinos Vaziourakis, Mona Abbasi, Elizabeth Jakobsson, Marloes Groeneveld, Sarah Shakil, and Jeffrey Hawkes for helpful discussions throughout the development and writing of this manuscript.

Financial support

This work was supported by the Knut and Alice Wallenberg Foundation. DK was funded from the Swedish National Science Foundation (VR 2020-03249).

References (in text)

Abbott, B. W., Larouche, J. R., Jones, J. J. B., Bowden, W. B., & Balser, A. W. (2014). From Thawing and Collapsing Permafrost. *Journal of Geophysical Research: Biogeosciences*, *119*, 2049–2063. https://doi.org/10.1002/2014JG002678.Received

Aitkenhead, J. A., & McDowell, W. H. (2000). Soil C:N ratio as a predictor of annual riverine DOC flux at local and global scales. *Global Biogeochemical Cycles*, *14*(1). https://doi.org/10.1029/1999GB900083

Amon, R. M. W., Rinehart, A. J., Duan, S., Louchouarn, P., Prokushkin, A., Guggenberger, G., … Zhulidov, A. V. (2012). Dissolved organic matter sources in large Arctic rivers. *Geochimica et Cosmochimica Acta*, *94*, 217–237. https://doi.org/https://doi.org/10.1016/j.gca.2012.07.015

Andersen, C.M. and Bro, R. (2010), Variable selection in regression—a tutorial. J. Chemometrics, 24: 728-737. https://doi.org/10.1002/cem.1360

Andresen, C. G., Lawrence, D. M., Wilson, C. J., McGuire, A. D., Koven, C., Schaefer, K., Jafarov, E., Peng, S., Chen, X., Gouttevin, I., Burke, E., Chadburn, S., Ji, D., Chen, G., Hayes, D., and Zhang, W.: Soil moisture and hydrology projections of the permafrost region – a model intercomparison, The Cryosphere, 14, 445–459, https://doi.org/10.5194/tc-14-445-2020, 2020.

Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a methodological framework. *International Journal of Social Research Methodology: Theory and Practice*, *8*(1). https://doi.org/10.1080/1364557032000119616

Attermeyer, K., Catalán, N., Einarsdottir, K., Freixa, A., Groeneveld, M., Hawkes, J. A., … Tranvik, L. J. (2018). Organic Carbon Processing During Transport Through Boreal Inland Waters: Particles as Important Sites. *Journal of Geophysical Research: Biogeosciences*, *123*(8). https://doi.org/10.1029/2018JG004500

Beckebanze, L., Runkle, B. R. K., Walz, J., Wille, C., Holl, D., Helbig, M., … Kutzbach, L. (2022). Lateral carbon export has low impact on the net ecosystem carbon balance of a polygonal tundra catchment. *BIOGEOSCIENCES*, *19*(16), 3863–3876. https://doi.org/10.5194/bg-19-3863-2022

Beer, J., Lee, K., Whiticar, M., & Blodau, C. (2008). Geochemical controls on anaerobic organic matter decomposition in a northern peatland. *Limnology and Oceanography*, *53*(4), 1393–1407. https://doi.org/10.4319/lo.2008.53.4.1393

Formatted: Normal (Web), Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Formatted: Font color: Auto

Formatted: Font color: Red, Check spelling and grammar

Biester, H., Knorr, K. H., Schellekens, J., Basler, A., & Hermanns, Y. M. (2014). Comparison of different methods to determine the degree of peat decomposition in peat bogs. *Biogeosciences*. https://doi.org/10.5194/bg-11-2691-2014

Blodau, C. (2002). Carbon cycling in peatlands — A review of processes and controls. *Environmental Reviews*, *10*(2), 111–134. https://doi.org/10.1139/a02-004

Bolan, N.S., Baskaran, S., Thiagarajan, S. (1999). Methods of Measurement of Dissolved Organic Carbon of Plant Origin in Soils, Manures, Sludges and Stream Water. In: Linskens, H.F., Jackson, J.F. (eds) Analysis of Plant Waste Materials. Modern Methods of Plant Analysis, vol 20. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-03887-1_1

Bristol, E. M., Connolly, C. T., Lorenson, T. D., Richmond, B. M., Ilgen, A. G., Choens, R. C., … McClelland, J. W. (2021). Geochemistry of Coastal Permafrost and Erosion-Driven Organic Matter Fluxes to the Beaufort Sea Near Drew Point, Alaska. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.598933

Bröder, L., Hirst, C., Opfergelt, S., Thomas, M., Vonk, J. E., Haghipour, N., … Fouché, J. (2022). Contrasting Export of Particulate Organic Carbon From Greenlandic Glacial and Nonglacial Streams. *Geophysical Research Letters*, *49*(21). https://doi.org/10.1029/2022GL101210

Brown, J., Ferrians Jr., O. J., Heginbottom, J. A., & Melnikov, E. S. (1997). Circum-Arctic map of permafrost and ground ice conditions. *USGS Numbered Series*, 1. https://doi.org/10.1016/j.jallcom.2010.03.054

Bruhn, A. D., Stedmon, C. A., Comte, J., Matsuoka, A., Speetjens, N. J., Tanski, G., … Sjöstedt, J. (2021). Terrestrial Dissolved Organic Matter Mobilized From Eroding Permafrost Controls Microbial Community Composition and Growth in Arctic Coastal Zones. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.640580

Burd, K., Estop-Aragonés, C., Tank, S. E., & Olefeldt, D. (2020). Lability of dissolved organic carbon from boreal peatlands: interactions between permafrost thaw, wildfire, and season. *Canadian Journal of Soil Science*, *13*(February), 1–13. https://doi.org/10.1139/cjss-2019-0154

Camill, P. (2005). Permafrost thaw accelerates in boreal peatlands during late-20th century climate warming. *Climatic Change*, *68*(1–2), 135–152. https://doi.org/10.1007/s10584-005-4785-y

Chanton, J. P., Glaser, P. H., Chasar, L. S., Burdige, D. J., Hines, M. E., Siegel, D. I., … Cooper, W. T. (2008). Radiocarbon evidence for the importance of surface vegetation on fermentation and methanogenesis in contrasting types of boreal peatlands. *Global Biogeochemical Cycles*, *22*(4), 1–11. https://doi.org/10.1029/2008GB003274

Chen, H., Yang, Z., Chu, R. K., Tolic, N., Liang, L., Graham, D. E., … Gu, B. (2018). Molecular Insights into Arctic Soil Organic Matter Degradation under Warming. *ENVIRONMENTAL SCIENCE & TECHNOLOGY*, *52*(8), 4555–4564. https://doi.org/10.1021/acs.est.7b05469

Chong, I. G., & Jun, C. H. (2005). Performance of some variable selection methods when multicollinearity is present. *Chemometrics and Intelligent Laboratory Systems*, *78*(1). https://doi.org/10.1016/j.chemolab.2004.12.011\

Connon, R. F., Quinton, W. L., Craig, J. R., & Hayashi, M. (2014). Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada. *Hydrological Processes*, *28*(14). https://doi.org/10.1002/hyp.10206

Dean, J. F., Meisel, O. H., Rosco, M. M., Marchesini, L. B., Garnett, M. H., Lenderink, H., … Dolman, A. J. (2020). East Siberian Arctic inland waters emit mostly contemporary carbon. *NATURE COMMUNICATIONS*, *11*(1). https://doi.org/10.1038/s41467-020-15511-6

Drake, T. W., Wickland, K. P., Spencer, R. G. M., McKnight, D. M., & Striegl, R. G. (2015). Ancient low-molecular-weight organic acids in permafrost fuel rapid carbon dioxide production upon thaw. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA*, *112*(45), 13946–13951. https://doi.org/10.1073/pnas.1511705112

Ernakovich, J. G., Lynch, L. M., Brewer, P. E., Calderon, F. J., & Wallenstein, M. D. (2017). Redox and temperature-sensitive changes in microbial communities and soil chemistry dictate greenhouse gas loss from thawed permafrost. *BIOGEOCHEMISTRY*, *134*(1–2), 183–200. https://doi.org/10.1007/s10533-017-0354-5

Estop-Aragones, C., Olefeldt, D., Abbott, B. W., Chanton, J. P., Czimczik, C. I., Dean, J. F., … Anthony, K. W. (2020). Assessing the Potential for Mobilization of Old Soil Carbon After Permafrost Thaw: A Synthesis of C-14 Measurements From the Northern Permafrost Region. *GLOBAL BIOGEOCHEMICAL CYCLES*, *34*(9). https://doi.org/10.1029/2020GB006672

Estop-Aragonés, Cristian, Czimczik, C. I., Heffernan, L., Gibson, C., Walker, J. C., Xu, X., & Olefeldt, D. (2018). Respiration of aged soil carbon during fall in permafrost peatlands enhanced by active layer deepening following wildfire but limited following thermokarst. *Environmental Research Letters*, *13*(8). https://doi.org/10.1088/1748-9326/aad5f0

Ewing, S. A., Paces, J. B., O'Donnell, J. A., Jorgenson, M. T., Kanevskiy, M. Z., Aiken, G. R., … Striegl, R. (2015a). Uranium isotopes and dissolved organic carbon in loess permafrost: Modeling the age of ancient ice. *GEOCHIMICA ET COSMOCHIMICA ACTA*, *152*, 143–165. https://doi.org/10.1016/j.gca.2014.11.008

Ewing, S. A., Paces, J. B., O'Donnell, J. A., Jorgenson, M. T., Kanevskiy, M. Z., Aiken, G. R., … Striegl, R. (2015b). Uranium isotopes and dissolved organic carbon in loess permafrost:

Formatted: Font: Check spelling and grammar

Formatted: Indent: Left: 0 cm, First line: 0 cm, Space After: 0 pt, Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Formatted: Normal (Web), Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Modeling the age of ancient ice. *Geochimica et Cosmochimica Acta*, *152*, 143–165. https://doi.org/10.1016/j.gca.2014.11.008

Fouché, J., Christiansen, C. T., Lafrenière, M. J., Grogan, P., & Lamoureux, S. F. (2020). Canadian permafrost stores large pools of ammonium and optically distinct dissolved organic matter. *Nature Communications*, *11*(1), 4500. https://doi.org/10.1038/s41467-020-18331-w

Fritz, M., Vonk, J. E., & Lantuit, H. (2017). Collapsing Arctic coastlines. *Nature Climate Change*. https://doi.org/10.1038/nclimate3188

Gentsch, N., Mikutta, R., Shibistova, O., Wild, B., Schnecker, J., Richter, A., … Guggenberger, G. (2015). Properties and bioavailability of particulate and mineral-associated organic matter in Arctic permafrost soils, Lower Kolyma Region, Russia. *European Journal of Soil Science*, *66*(4). https://doi.org/10.1111/ejss.12269

Guggenberger, G., & Zech, W. (1993). Dissolved organic carbon control in acid forest soils of the Fichtelgebirge (Germany) as revealed by distribution patterns and structural composition analyses. *Geoderma*, *59*(1–4). https://doi.org/10.1016/0016-7061(93)90065-S

Guggenberger, Georg, Rodionov, A., Shibistova, O., Grabe, M., Kasansky, O. A., Fuchs, H., … Flessa, H. (2008). Storage and mobility of black carbon in permafrost soils of the forest tundra ecotone in Northern Siberia. *Global Change Biology*, *14*(6), 1367–1381. https://doi.org/10.1111/j.1365-2486.2008.01568.x

Guo, Z., Wang, Y., Wan, Z., Zuo, Y., He, L., Li, D., … Xu, X. (2020). Soil dissolved organic carbon in terrestrial ecosystems: Global budget, spatial distribution and controls. *Global Ecology and Biogeography*, *29*(12). https://doi.org/10.1111/geb.13186

Hamard, S., Robroek, B. J. M., Allard, P. M., Signarbieux, C., Zhou, S., Saesong, T., … Jassey, V. E. J. (2019). Effects of Sphagnum Leachate on Competitive Sphagnum Microbiome Depend on Species and Time. *Frontiers in Microbiology*, *10*. https://doi.org/10.3389/fmicb.2019.02042

Hansen, A. M., Kraus, T. E. C., Pellerin, B. A., Fleck, J. A., Downing, B. D., & Bergamaschi, B. A. (2016). Optical properties of dissolved organic matter (DOM): Effects of biological and photolytic degradation. *Limnology and Oceanography*, **61**(3), 1015–1032. https://doi.org/10.1002/lno.10270

Heffernan, L., Cavaco, M. A., Bhatia, M. P., Estop-Aragonés, C., Knorr, K.-H., & Olefeldt, D. (2022). High peatland methane emissions following permafrost thaw: enhanced acetoclastic methanogenesis during early successional stages. *Biogeosciences*, *19*(12). https://doi.org/10.5194/bg-19-3051-2022

Heffernan, L., Estop-Aragonés, C., Knorr, K.-H., Talbot, J., & Olefeldt, D. (2020). Long-term impacts of permafrost thaw on carbon storage in peatlands: deep losses offset by surficial accumulation. *Journal of Geophysical Research: Biogeosciences*, *2011*(2865), e2019JG005501. https://doi.org/10.1029/2019JG005501

Heslop, J. K., Chandra, S., Sobzcak, W. V, Davydov, S. P., Davydova, A. I., Spektor, V. V, & Anthony, K. M. W. (2017). Variable respiration rates of incubated permafrost soil extracts from the Kolyma River lowlands, north-east Siberia. *POLAR RESEARCH*, *36*. https://doi.org/10.1080/17518369.2017.1305157

Holmes, R. M., McClelland, J. W., Peterson, B. J., Tank, S. E., Bulygina, E., Eglinton, T. I., … Zimov, S. A. (2012). Seasonal and Annual Fluxes of Nutrients and Organic Matter from Large Rivers to the Arctic Ocean and Surrounding Seas. *ESTUARIES AND COASTS*, *35*(2), 369–382. https://doi.org/10.1007/s12237-011-9386-6

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C. L., … Kuhry, P. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, *11*(23), 6573–6593. https://doi.org/10.5194/bg-11-6573-2014

Hugelius, Gustaf, Loisel, J., Chadburn, S., Jackson, R. B., Jones, M., MacDonald, G., … Yu, Z. (2020). Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proceedings of the National Academy of Sciences*, *117*(34), 20438–20446. https://doi.org/10.1073/pnas.1916387117

Hultman, J., Waldrop, M. P., Mackelprang, R., David, M. M., McFarland, J., Blazewicz, S. J., … Jansson, J. K. (2015). Multi-omics of permafrost, active layer and thermokarst bog soil microbiomes. *Nature*, *521*(7551). https://doi.org/10.1038/nature14238

Jorgenson, M. T., Shur, Y. L., & Pullman, E. R. (2006). Abrupt increase in permafrost degradation in Arctic Alaska. *Geophysical Research Letters*, *33*(2). https://doi.org/10.1029/2005GL024960

Kalbitz K, Sloinger S, Park JH, Michalzik B, Matzner E (2000) Controls on the dynamics of dissolved organic matter in soils: a review. Soil Science, 165, 277–304.

Kawahigashi, M., Kaiser, K., Rodionov, A., & Guggenberger, G. (2006). Sorption of dissolved organic matter by mineral soils of the Siberian forest tundra. *GLOBAL CHANGE BIOLOGY*, *12*(10), 1868–1877. https://doi.org/10.1111/j.1365-2486.2006.01203.x

Keskitalo, K. H., Bröder, L., Shakil, S., Zolkos, S., Tank, S. E., van Dongen, B. E., … Vonk, J. E. (2021). Downstream Evolution of Particulate Organic Matter Composition From Permafrost Thaw Slumps. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.642675

Kicklighter, D. W., Hayes, D. J., McClelland, J. W., Peterson, B. J., McGuire, A. D., & Melillo, J. M. (2013). Insights and issues with simulating terrestrial DOC loading of Arctic river networks. *ECOLOGICAL APPLICATIONS*, *23*(8), 1817–1836. https://doi.org/10.1890/11-

Formatted: Normal (Web), Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

1050.1

Kokelj, S. V., & Jorgenson, M. T. (2013). Advances in thermokarst research. *Permafrost and Periglacial Processes*, *24*(2), 108–119. https://doi.org/10.1002/ppp.1779

Lajeunesse, M. J. (2011). On the meta-analysis of response ratios for studies with correlated and multi-group designs. *Ecology*, *92*(11). https://doi.org/10.1890/11-0423.1

Lajtha, K., Crow, S. E., Yano, Y., Kaushal, S. S., Sulzman, E., Sollins, P., & Spears, J. D. H. (2005). Detrital controls on soil solution N and dissolved organic matter in soils: A field experiment. *Biogeochemistry*, *76*(2). https://doi.org/10.1007/s10533-005-5071-9

Lamit, L. J., Romanowicz, K. J., Potvin, L. R., Lennon, J. T., Tringe, S. G., Chimner, R. A., … Lilleskov, E. A. (2021). Peatland microbial community responses to plant functional group and drought are depth-dependent. *Molecular Ecology*, *30*(20). https://doi.org/10.1111/mec.16125

Langeveld, J., Bouwman, A. F., van Hoek, W. J., Vilmin, L., Beusen, A. H. W., Mogollón, J. M., & Middelburg, J. J. (2020). Estimating dissolved carbon concentrations in global soils: a global database and model. *SN Applied Sciences*, *2*(10), 1–21. https://doi.org/10.1007/s42452-020-03290-0

Lantuit, H., Overduin, P. P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D. L., & Graves-Gaylord, A. (2012). The Arctic coastal dynamics database: A new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries and Coasts*, 35(2), 383–400. https://doi.org/10.1007/s12237-010-9362-6

Lara, M. J., Nitze, I., Grosse, G., Martin, P., & David McGuire, A. (2018). Reduced arctic tundra productivity linked with landform and climate change interactions. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-20692-8

Liljedahl, A. K., Boike, J., Daanen, R. P., Fedorov, A. N., Frost, G. V., Grosse, G., … Zona, D. (2016). Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience*, *9*(4). https://doi.org/10.1038/ngeo2674

Limpens, J., Bohlin, E., & Nilsson, M. B. (2017). Phylogenetic or environmental control on the elemental and organo-chemical composition of Sphagnum mosses? *Plant and Soil*. https://doi.org/10.1007/s11104-017-3239-4

Loiko, S. V, Pokrovsky, O. S., Raudina, T. V, Lim, A., Kolesnichenko, L. G., Shirokova, L. S., … Kirpotin, S. N. (2017). Abrupt permafrost collapse enhances organic carbon, CO2, nutrient and metal release into surface waters. *Chemical Geology*, *471*, 153–165. https://doi.org/https://doi.org/10.1016/j.chemgeo.2017.10.002

Ma, Q., Jin, H., Yu, C., & Bense, V. F. (2019). Dissolved organic carbon in permafrost regions:

Formatted: Normal (Web), Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Formatted: Dutch (Netherlands)

A review. *Science China Earth Sciences*. https://doi.org/10.1007/s11430-018-9309-6

MacDonald, E. N., Tank, S. E., Kokelj, S. V., Froese, D. G., & Hutchins, R. H. S. (2021). Permafrost-derived dissolved organic matter composition varies across permafrost end-members in the western Canadian Arctic. *Environmental Research Letters*, *16*(2). https://doi.org/10.1088/1748-9326/abd971

Manies, K. L., Jones, M. C., Waldrop, M. P., Leewis, M. C., Fuller, C., Cornman, R. S., & Hoefke, K. (2021). Influence of Permafrost Type and Site History on Losses of Permafrost Carbon After Thaw. *Journal of Geophysical Research: Biogeosciences*, *126*(11). https://doi.org/10.1029/2021JG006396

Marschner B, Bredow A (2002) Temperature effects on release and ecologically relevant properties of dissolved organic carbon in sterilised and biologically active soil samples. Soil Biology and Biochemistry, 34, 459–466.

McGuire, A. D., Lawrence, D. M., Koven, C., Clein, J. S., Burke, E., Chen, G., … Zhuang, Q. (2018). Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(15). https://doi.org/10.1073/pnas.1719903115

Mehmood, T., Liland, K. H., Snipen, L., & Sæbø, S. (2012). A review of variable selection methods in Partial Least Squares Regression. *Chemometrics and Intelligent Laboratory Systems*. https://doi.org/10.1016/j.chemolab.2012.07.010

Mevik, B. H., & Wehrens, R. (2007). The pls package: Principal component and partial least squares regression in R. *Journal of Statistical Software*, *18*(2). https://doi.org/10.18637/jss.v018.i02

Miner, K. R., Turetsky, M. R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A. D., … Miller, C. E. (2022). Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth and Environment*. https://doi.org/10.1038/s43017-021-00230-3

Mohammed, A. A., Guimond, J. A., Bense, V. F., Jamieson, R. C., McKenzie, J. M., & Kurylyk, B. L. (2022). Mobilization of subsurface carbon pools driven by permafrost thaw and reactivation of groundwater flow: a virtual experiment. *Environmental Research Letters*, *17*(12), 124036. https://doi.org/10.1088/1748-9326/ACA701

Monteux, S., Weedon, J. T., Blume-Werry, G., Gavazov, K., Jassey, V. E. J., Johansson, M., … Dorrepaal, E. (2018). Long-term in situ permafrost thaw effects on bacterial communities and potential aerobic respiration. *ISME Journal*, *12*(9), 2129–2141. https://doi.org/10.1038/s41396-018-0176-z

Moore, T. R., & Dalva, M. (2001). Some controls on the release of dissolved organic carbon by plant tissues and soils. *Soil Science*, *166*(1), 38–47. https://doi.org/10.1097/00010694-200101000-00007

Neff, J. C., & Hooper, D. U. (2002). Vegetation and climate controls on potential CO2, DOC and DON production in northern latitude soils. *Global Change Biology*, *8*(9), 872–884. https://doi.org/10.1046/j.1365-2486.2002.00517.x

O'Donnell, J. A., Aiken, G. R., Butler, K. D., Guillemette, F., Podgorski, D. C., & Spencer, R. G. M. (2016). DOM composition and transformation in boreal forest soils: The effects of temperature and organic-horizon decomposition state. *Journal of Geophysical Research: Biogeosciences*, *121*(10), 2727–2744. https://doi.org/10.1002/2016JG003431.Received

Olefeldt, D., Heffernan, L., Jones, M. C., Sannel, A. B. K., Treat, C. C., & Turetsky, M. R. (2021). Permafrost Thaw in Northern Peatlands: Rapid Changes in Ecosystem and Landscape Functions (pp. 27–67). https://doi.org/10.1007/978-3-030-71330-0_3

Olefeldt, D., & Roulet, N. T. (2012). Effects of permafrost and hydrology on the composition and transport of dissolved organic carbon in a subarctic peatland complex. *Journal of Geophysical Research: Biogeosciences*, *117*(1). https://doi.org/10.1029/2011JG001819

Olefeldt, D., & Roulet, N. T. (2014). Permafrost conditions in peatlands regulate magnitude, timing, and chemical composition of catchment dissolved organic carbon export. *GLOBAL CHANGE BIOLOGY*, *20*(10), 3122–3136. https://doi.org/10.1111/gcb.12607

Olefeldt, D., Roulet, N. T., Bergeron, O., Crill, P., Bäckstrand, K., & Christensen, T. R. (2012). Net carbon accumulation of a high-latitude permafrost palsa mire similar to permafrost-free peatlands. *Geophysical Research Letters*, *39*(3). https://doi.org/10.1029/2011GL050355

Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., … Turetsky, M. R. (2016). Circumpolar distribution and carbon storage of thermokarst landscapes. Nature Communications, 7, 13043. https://doi.org/10.1038/ncomms13043

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., … others. (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience*, *51*(11).

Panneer Selvam, B., Lapierre, J.-F., Guillemette, F., Voigt, C., Lamprecht, R. E., Biasi, C., … Berggren, M. (2017). Degradation potentials of dissolved organic carbon (DOC) from thawed permafrost peat. *SCIENTIFIC REPORTS*, *7*, 45811. https://doi.org/10.1038/srep45811

Parmentier, FJ.W., Christensen, T.R., Rysgaard, S. et al. A synthesis of the arctic terrestrial and marine carbon cycles under pressure from a dwindling cryosphere. Ambio 46 (Suppl 1), 53–69 (2017). https://doi.org/10.1007/s13280-016-0872-8

Payandi-Rolland, D., Shirokova, L. S., Tesfa, M., Bénézeth, P., Lim, A. G., Kuzmina, D., … Pokrovsky, O. S. (2020). Dissolved organic matter biodegradation along a hydrological

Formatted: English (United States)

Formatted: Normal (Web), Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

continuum in permafrost peatlands. *Science of The Total Environment*, *749*, 141463. https://doi.org/10.1016/J.SCITOTENV.2020.141463

Peacock, M., Futter, M. N., Jutterström, S., Kothawala, D. N., Moldan, F., Stadmark, J., & Evans, C. D. (2022). Three Decades of Changing Nutrient Stoichiometry from Source to Sea on the Swedish West Coast. *Ecosystems*, *25*(8). https://doi.org/10.1007/s10021-022-00798-x

Pries, C. E. H., Schuur, E. A. G., & Crummer, K. G. (2012). Holocene Carbon Stocks and Carbon Accumulation Rates Altered in Soils Undergoing Permafrost Thaw. *Ecosystems*, *15*(1). https://doi.org/10.1007/s10021-011-9500-4

Prokushkin, A. S., Gavrilenko, I. V., Abaimov, A. P., Prokushkin, S. G., & Samusenko, A. V. (2006). Dissolved organic carbon in upland forested watersheds underlain by continuous permafrost in Central Siberia. *Mitigation and Adaptation Strategies for Global Change*, *11*(1), 223–240. https://doi.org/10.1007/s11027-006-1022-6

Prokushkin, A S, Kajimoto, T., Prokushkin, S. G., McDowell, W. H., Abaimov, A. P., & Matsuura, Y. (2005). Climatic factors influencing fluxes of dissolved organic carbon from the forest floor in a continuous-permafrost Siberian watershed. *CANADIAN JOURNAL OF FOREST RESEARCH*, *35*(9), 2130–2140. https://doi.org/10.1139/X05-150

Prokushkin, Anatoly S., Kawahigashi, M., & Tokareva, I. V. (2008). Global Warming and Dissolved Organic Carbon Release from Permafrost Soils. In *Permafrost Soils* (pp. 237–250). https://doi.org/10.1007/978-3-540-69371-0_16

Quinton, W. L., Hayashi, M., & Chasmer, L. E. (2011). Permafrost-thaw-induced land-cover change in the Canadian subarctic: Implications for water resources. *Hydrological Processes*, *25*(1), 152–158. https://doi.org/10.1002/hyp.7894

Quinton, W. L., Hayashi, M., & Pietroniro, A. (2003). Connectivity and storage functions of channel fens and flat bogs in northern basins. *Hydrological Processes*. https://doi.org/10.1002/hyp.1369

Rantanen, M., Karpechko, A., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., … Laaksonen, A. (2021). The Arctic has warmed four times faster than the globe since 1980. *Nature Portfolio*, (2022), 0–29. https://doi.org/https://doi.org/10.1038/s43247-022-00498-3

Raymond, P. A., McClelland, J. W., Holmes, R. M., Zhulidov, A. V., Mull, K., Peterson, B. J., … Gurtovaya, T. Y. (2007). Flux and age of dissolved organic carbon exported to the Arctic Ocean: A carbon isotopic study of the five largest arctic rivers. *Global Biogeochemical Cycles*, *21*(4). https://doi.org/10.1029/2007GB002934

Ripley, B., Venables, B., Bates, D. M., Hornik, K., Gebhardt, A., & Firth, D. (2019). Package 'MASS' (Version 7.3-51.4). *Cran-R Project*.

Schaefer, K., Lantuit, H., Romanovsky, V. E., Schuur, E. A. G., & Witt, R. (2014). The impact of the permafrost carbon feedback on global climate. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/9/8/085003

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., Loranty, 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, 343–371.

Schuur, E. A. G., Bracho, R., Celis, G., Belshe, E. F., Ebert, C., Ledman, J., … Webb, E. E. (2021). Tundra Underlain By Thawing Permafrost Persistently Emits Carbon to the Atmosphere Over 15 Years of Measurements. *Journal of Geophysical Research: Biogeosciences*, *126*(6), 1–23. https://doi.org/10.1029/2020jg006044

Schuur, T., McGuire, A. D., Romanovsky, V., Schädel, C., & Mack, M. (2018). Chapter 11: Arctic and Boreal Carbon. Second State of the Carbon Cycle Report. *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*, 428–468. Retrieved from https://carbon2018.globalchange.gov/chapter/11/

Selvam, B. P., Lapierre, J.-F., Guillemette, F., Voigt, C., Lamprecht, R. E., Biasi, C., … Berggren, M. (2017). Degradation potentials of dissolved organic carbon (DOC) from thawed permafrost peat. *SCIENTIFIC REPORTS*, *7*. https://doi.org/10.1038/srep45811

Semenchuk, P. R., Elberling, B., Amtorp, C., Winkler, J., Rumpf, S., Michelsen, A., & Cooper, E. J. (2015). Deeper snow alters soil nutrient availability and leaf nutrient status in high Arctic tundra. *Biogeochemistry*, *124*(1–3), 81–94. https://doi.org/10.1007/s10533-015-0082-7

Shakil, S., Tank, S. E., Kokelj, S. V., Vonk, J. E., & Zolkos, S. (2020). Particulate dominance of organic carbon mobilization from thaw slumps on the Peel Plateau, NT: Quantification and implications for stream systems and permafrost carbon release. *Environmental Research Letters*, *15*(11). https://doi.org/10.1088/1748-9326/abac36

Sobek, S., Tranvik, L. J., Prairie, Y. T., Kortelainen, P., & Cole, J. J. (2007). Patterns and regulation of dissolved organic carbon: An analysis of 7,500 widely distributed lakes. *Limnology and Oceanography*, *52*(3). https://doi.org/10.4319/lo.2007.52.3.1208

Speetjens, N. J., Tanski, G., Martin, V., Wagner, J., Richter, A., Hugelius, G., … Vonk, J. E. (2022). Dissolved organic matter characterization in soils and streams in a small coastal low-arctic catchment. *Biogeosciences*, *19*(July), 3073–3097. Retrieved from https://doi.org/10.5194/bg-19-3073-2022

Stolpmann, L., Coch, C., Morgenstern, A., Boike, J., Fritz, M., Herzschuh, U., … Grosse, G. (2021). First pan-Arctic assessment of dissolved organic carbon in lakes of the permafrost region. *BIOGEOSCIENCES*, *18*(12), 3917–3936. https://doi.org/10.5194/bg-18-3917-2021

Formatted: English (United States)

Strauss, J., Laboor, S., Schirrmeister, L., Fedorov, A. N., Fortier, D., Froese, D., … Grosse, G. (2021). Circum-Arctic Map of the Yedoma Permafrost Domain. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.758360

Striegl, R. G., Aiken, G. R., Dornblaser, M. M., Raymond, P. A., & Wickland, K. P. (2005). A decrease in discharge-normalized DOC export by the Yukon River during summer through autumn. *GEOPHYSICAL RESEARCH LETTERS*, *32*(21). https://doi.org/10.1029/2005GL024413

Tank, S. E., Frey, K. E., Striegl, R. G., Raymond, P. A., Holmes, R. M., McClelland, J. W., & Peterson, B. J. (2012). Landscape-level controls on dissolved carbon flux from diverse catchments of the circumboreal. *GLOBAL BIOGEOCHEMICAL CYCLES*, *26*. https://doi.org/10.1029/2012GB004299

Tanski, G., Wagner, D., Knoblauch, C., Fritz, M., Sachs, T., & Lantuit, H. (2019). Rapid CO2 Release From Eroding Permafrost in Seawater. *Geophysical Research Letters*, *46*(20). https://doi.org/10.1029/2019GL084303

Tanski, George, Bröder, L., Wagner, D., Knoblauch, C., Lantuit, H., Beer, C., … Vonk, J. E. (2021). Permafrost Carbon and CO2 Pathways Differ at Contrasting Coastal Erosion Sites in the Canadian Arctic. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.630493

Textor, S. R., Wickland, K. P., Podgorski, D. C., Johnston, S. E., & Spencer, R. G. M. (2019). Dissolved Organic Carbon Turnover in Permafrost-Influenced Watersheds of Interior Alaska: Molecular Insights and the Priming Effect. *FRONTIERS IN EARTH SCIENCE*, *7*. https://doi.org/10.3389/feart.2019.00275

Tfaily, M. M., Hamdan, R., Corbett, J. E., Chanton, J. P., Glaser, P. H., & Cooper, W. T. (2013). Investigating dissolved organic matter decomposition in northern peatlands using complimentary analytical techniques. *Geochimica et Cosmochimica Acta*. https://doi.org/10.1016/j.gca.2013.03.002

Thurman, E. M. (1985). Organic geochemistry of natural waters (Vol. 2). Springer Science & Business Media.

Treat, C. C., Jones, M. C., Camill, P., Gallego-Sala, A., Garneau, M., Harden, J. W., … Väliranta, M. (2016). Effects of permafrost aggradation on peat properties as determined from a pan-Arctic synthesis of plant macrofossils. *Journal of Geophysical Research: Biogeosciences*, *121*(1), 78–94. https://doi.org/10.1002/2015JG003061

Treat, Claire C., & Jones, M. C. (2018). Near-surface permafrost aggradation in Northern Hemisphere peatlands shows regional and global trends during the past 6000 years. *Holocene*. https://doi.org/10.1177/0959683617752858

Turetsky, M. R., Wieder, R. K., Vitt, D. H., Evans, R. J., & Scott, K. D. (2007). The

Formatted: Normal (Web), Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

disappearance of relict permafrost in boreal north America: Effects on peatland carbon storage and fluxes. *Global Change Biology*, *13*(9), 1922–1934. https://doi.org/10.1111/j.1365-2486.2007.01381.x

Turetsky, Merritt R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., … McGuire, A. D. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*. https://doi.org/10.1038/s41561-019-0526-0

USDA. (1999). *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys, 2nd Edition*. *Landscape and Land Capacity*.

Varner, R. K., Crill, P. M., Frolking, S., McCalley, C. K., Burke, S. A., Chanton, J. P., … Palace, M. W. (2022). Permafrost thaw driven changes in hydrology and vegetation cover increase trace gas emissions and climate forcing in Stordalen Mire from 1970 to 2014. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *380*(2215). https://doi.org/10.1098/rsta.2021.0022

Vonk, J E, Tank, S. E., Mann, P. J., Spencer, R. G. M., Treat, C. C., Striegl, R. G., … Wickland, K. P. (2015). Biodegradability of dissolved organic carbon in permafrost soils and aquatic systems: a meta-analysis. *BIOGEOSCIENCES*, *12*(23), 6915–6930. https://doi.org/10.5194/bg-12-6915-2015

Vonk, Jorien E., & Gustafsson, Ö. (2013). Permafrost-carbon complexities. *Nature Geoscience*. https://doi.org/10.1038/ngeo1937

Vonk, J. E., Mann, P. J., Davydov, S., Davydova, A., Spencer, R. G. M., Schade, J., … Holmes, R. M. (2013). High biolability of ancient permafrost carbon upon thaw. *GEOPHYSICAL RESEARCH LETTERS*, *40*(11), 2689–2693. https://doi.org/10.1002/grl.50348

Wang JA, Sulla-Menashe D, Woodcock CE, Sonnentag O, Keeling RF, Friedl MA. Extensive land cover change across Arctic–Boreal Northwestern North America from disturbance and climate forcing. Glob Change Biol. 2020; 26: 807–822. https://doi.org/10.1111/gcb.14804

Weishaar, J. L., Aiken, G. R., Bergamaschi, B. A., Fram, M. S., Fujii, R., & Mopper, K. (2003). Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon. Environmental Science and Technology, 37(20), 4702–4708. https://doi.org/10.1021/es030360x

Weyhenmeyer, G. A., Fröberg, M., Karltun, E., Khalili, M., Kothawala, D., Temnerud, J., & Tranvik, L. J. (2012). Selective decay of terrestrial organic carbon during transport from land to sea. *Global Change Biology*, *18*(1). https://doi.org/10.1111/j.1365-2486.2011.02544.x

Wickland, K.P., Neff, J. C., & Aiken, G. R. (2007). Dissolved organic carbon in Alaskan boreal forest: Sources, chemical characteristics, and biodegradability. *Ecosystems*, *10*(8), 1323–1340. https://doi.org/10.1007/s10021-007-9101-4

Formatted: Normal (Web), Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Formatted: English (Canada)

Wickland, Kimberly P, Waldrop, M. P., Aiken, G. R., Koch, J. C., Jorgenson, Mt., & Striegl, R. G. (2018). Dissolved organic carbon and nitrogen release from boreal Holocene permafrost and seasonally frozen soils of Alaska. *ENVIRONMENTAL RESEARCH LETTERS*, *13*(6). https://doi.org/10.1088/1748-9326/aac4ad

Wild, B., Andersson, A., Broder, L., Vonk, J., Hugelius, G., McClelland, J. W., … Gustafsson, O. (2019). Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing permafrost. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA*, *116*(21), 10280–10285. https://doi.org/10.1073/pnas.1811797116

Wild, B., Gentsch, N., Capek, P., Diáková, K., Alves, R. J. E., Bárta, J., … Richter, A. (2016). Plant-derived compounds stimulate the decomposition of organic matter in arctic permafrost soils. *Scientific Reports*, *6*. https://doi.org/10.1038/srep25607

Wild, B., Schnecker, J., Bárta, J., Čapek, P., Guggenberger, G., Hofhansl, F., … Richter, A. (2013). Nitrogen dynamics in Turbic Cryosols from Siberia and Greenland. *Soil Biology and Biochemistry*, *67*, 85–93. https://doi.org/https://doi.org/10.1016/j.soilbio.2013.08.004

Woo, M. (1986). Permafrost hydrology in north america. *Atmosphere - Ocean*, *24*(3). https://doi.org/10.1080/07055900.1986.9649248

Studies used to generate database

Abbott, B. W., Jones, J. B., Godsey, S. E., Larouche, J. R., & Bowden, W. B. (2015). Patterns and persistence of hydrologic carbon and nutrient export from collapsing upland permafrost. *Biogeosciences*, *12*(12), 3725–3740. https://doi.org/10.5194/bg-12-3725-2015

Abbott, B. W., Larouche, J. R., Jones, J. J. B., Bowden, W. B., & Balser, A. W. (2014). From Thawing and Collapsing Permafrost. *Journal of Geophysical Research: Biogeosciences*, *119*, 2049–2063. https://doi.org/10.1002/2014JG002678.Received

Beckebanze, L., Runkle, B. R. K., Walz, J., Wille, C., Holl, D., Helbig, M., … Kutzbach, L. (2022). Lateral carbon export has low impact on the net ecosystem carbon balance of a polygonal tundra catchment. *BIOGEOSCIENCES*, *19*(16), 3863–3876. https://doi.org/10.5194/bg-19-3863-2022

Boddy, E., Roberts, P., Hill, P. W., Farrar, J., & Jones, D. L. (2008). Turnover of low molecular weight dissolved organic C (DOC) and microbial C exhibit different temperature sensitivities in Arctic tundra soils. *SOIL BIOLOGY & BIOCHEMISTRY*, *40*(7), 1557–1566. https://doi.org/10.1016/j.soilbio.2008.01.030

Bristol, E. M., Connolly, C. T., Lorenson, T. D., Richmond, B. M., Ilgen, A. G., Choens, R. C., … McClelland, J. W. (2021). Geochemistry of Coastal Permafrost and Erosion-Driven Organic Matter Fluxes to the Beaufort Sea Near Drew Point, Alaska. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.598933

Bruhn, A. D., Stedmon, C. A., Comte, J., Matsuoka, A., Speetjens, N. J., Tanski, G., … Sjöstedt, J. (2021). Terrestrial Dissolved Organic Matter Mobilized From Eroding Permafrost Controls Microbial Community Composition and Growth in Arctic Coastal Zones. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.640580

Buckeridge, K. M., & Grogan, P. (2008). Deepened snow alters soil microbial nutrient limitations in arctic birch hummock tundra. *Applied Soil Ecology*, *39*(2), 210–222. https://doi.org/https://doi.org/10.1016/j.apsoil.2007.12.010

Burd, K., Estop-Aragonés, C., Tank, S. E., & Olefeldt, D. (2020). Lability of dissolved organic carbon from boreal peatlands: interactions between permafrost thaw, wildfire, and season. *Canadian Journal of Soil Science*, *13*(February), 1–13. https://doi.org/10.1139/cjss-2019-0154

Burd, K., Tank, S. E., Dion, N., Quinton, W. L., Spence, C., Tanentzap, A. J., & Olefeldt, D. (2018). Seasonal shifts in export of DOC and nutrients from burned and unburned peatland-rich catchments, Northwest Territories, Canada. *Hydrology and Earth System Sciences*, 4455–4472. https://doi.org/10.5194/hess-22-4455-2018

Carey, S. K. (2003). Dissolved organic carbon fluxes in a discontinuous permafrost subarctic alpine catchment. *PERMAFROST AND PERIGLACIAL PROCESSES*, *14*(2), 161–171. https://doi.org/10.1002/ppp.444

Chiasson-Poirier, G., Franssen, J., Lafreniere, M. J., Fortier, D., & Lamoureux, S. F. (2020). Seasona evolution of active layer thaw depth and hillslope-stream connectivity in a permafrost watershed. *WATER RESOURCES RESEARCH*, *56*(1). https://doi.org/10.1029/2019WR025828

Connolly, C. T., Cardenas, M. B., Burkart, G. A., Spencer, R. G. M., & McClelland, J. W. (2020). Groundwater as a major source of dissolved organic matter to Arctic coastal waters. *NATURE COMMUNICATIONS*, *11*(1). https://doi.org/10.1038/s41467-020-15250-8

Cory, R. M., Crump, B. C., Dobkowski, J. A., & Kling, G. W. (2013). Surface exposure to sunlight stimulates CO_2 release from permafrost soil carbon in the Arctic. *Proceedings of the National Academy of Sciences*, *110*(9), 3429–3434. https://doi.org/10.1073/pnas.1214104110

Deshpande, B. N., Crevecoeur, S., Matveev, A., & Vincent, W. F. (2016). Bacterial production in subarctic peatland lakes enriched by thawing permafrost. *BIOGEOSCIENCES*, *13*(15), 4411–4427. https://doi.org/10.5194/bg-13-4411-2016

Douglas, T. A., Fortier, D., Shur, Y. L., Kanevskiy, M. Z., Guo, L., Cai, Y., & Bray, M. T. (2011). Biogeochemical and Geocryological Characteristics of Wedge and Thermokarst-Cave Ice in the CRREL Permafrost Tunnel, Alaska. *PERMAFROST AND PERIGLACIAL PROCESSES*, *22*(2), 120–128. https://doi.org/10.1002/ppp.709

Drake, T. W., Wickland, K. P., Spencer, R. G. M., McKnight, D. M., & Striegl, R. G. (2015). Ancient low-molecular-weight organic acids in permafrost fuel rapid carbon dioxide production upon thaw. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA*, *112*(45), 13946–13951. https://doi.org/10.1073/pnas.1511705112

Dutta, K., Schuur, E. A. G., Neff, J. C., & Zimov, S. A. (2006). Potential carbon release from permafrost soils of Northeastern Siberia. *GLOBAL CHANGE BIOLOGY*, *12*(12), 2336–2351. https://doi.org/10.1111/j.1365-2486.2006.01259.x

Edwards, K. A., & Jefferies, R. L. (2013). Inter-annual and seasonal dynamics of soil microbial biomass and nutrients in wet and dry low-Arctic sedge meadows. *Soil Biology and Biochemistry*, *57*, 83–90. https://doi.org/https://doi.org/10.1016/j.soilbio.2012.07.018

Edwards, K. A., McCulloch, J., Kershaw], G. [Peter, & Jefferies, R. L. (2006). Soil microbial and nutrient dynamics in a wet Arctic sedge meadow in late winter and early spring. *Soil Biology and Biochemistry*, *38*(9), 2843–2851. https://doi.org/https://doi.org/10.1016/j.soilbio.2006.04.042

Ernakovich, J. G., Lynch, L. M., Brewer, P. E., Calderon, F. J., & Wallenstein, M. D. (2017). Redox and temperature-sensitive changes in microbial communities and soil chemistry dictate greenhouse gas loss from thawed permafrost. *BIOGEOCHEMISTRY*, *134*(1–2), 183–200. https://doi.org/10.1007/s10533-017-0354-5

Ewing, S. A., Paces, J. B., O'Donnell, J. A., Jorgenson, M. T., Kanevskiy, M. Z., Aiken, G. R., … Striegl, R. (2015). Uranium isotopes and dissolved organic carbon in loess permafrost: Modeling the age of ancient ice. *GEOCHIMICA ET COSMOCHIMICA ACTA*, *152*, 143–165. https://doi.org/10.1016/j.gca.2014.11.008

Fenger-Nielsen, R., Hollesen, J., Matthiesen, H., Andersen, E. A. S., Westergaard-Nielsen, A., Harmsen, H., … Elberling, B. (2019). Footprints from the past: The influence of past human activities on vegetation and soil across five archaeological sites in Greenland. *Science of the Total Environment*, *654*, 895–905. https://doi.org/10.1016/j.scitotenv.2018.11.018

Fouché, J., Christiansen, C. T., Lafrenière, M. J., Grogan, P., & Lamoureux, S. F. (2020). Canadian permafrost stores large pools of ammonium and optically distinct dissolved organic matter. *Nature Communications*, *11*(1), 4500. https://doi.org/10.1038/s41467-020-18331-w

Fouche, J., Bouchez, C., Keller, C., Allard, M., & Ambrosi, J.-P. (2021). Seasonal cryogenic processes control supra-permafrost pore water chemistry in two contrasting Cryosols. *GEODERMA*, *401*. https://doi.org/10.1016/j.geoderma.2021.115302

Fouché, J., Keller, C., Allard, M., Ambrosi, J. P., Fouche, J., Keller, C., … Ambrosi, J. P. (2014). Increased CO2 fluxes under warming tests and soil solution chemistry in Histic and Turbic Cryosols, Salluit, Nunavik, Canada. *Soil Biology and Biochemistry*, *68*, 185–199. https://doi.org/https://doi.org/10.1016/j.soilbio.2013.10.007

Fritz, M., Opel, T., Tanski, G., Herzschuh, U., Meyer, H., Eulenburg, A., & Lantuit, H. (2015). Dissolved organic carbon (DOC) in Arctic ground ice. *CRYOSPHERE*, *9*(2), 737–752. https://doi.org/10.5194/tc-9-737-2015

Gagné, K. R., Ewers, S. C., Murphy, C. J., Daanen, R., Walter Anthony, K., & Guerard, J. J. (2020). Composition and photo-reactivity of organic matter from permafrost soils and surface waters in interior Alaska. *Environmental Science: Processes and Impacts*, *22*(7), 1525–1539. https://doi.org/10.1039/d0em00097c

Gao, L., Zhou, Z., Reyes V, A., & Guo, L. (2018). Yields and Characterization of Dissolved Organic Matter From Different Aged Soils in Northern Alaska. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *123*(7), 2035–2052. https://doi.org/10.1029/2018JG004408

Herndon, E. M., Mann, B. F., Chowdhury, T. R., Yang, Z., Wullschleger, S. D., Graham, D., … Gu, B. (2015). Pathways of anaerobic organic matter decomposition in tundra soils from Barrow, Alaska. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *120*(11), 2345–2359. https://doi.org/10.1002/2015JG003147

Herndon, E. M., Yang, Z., Bargar, J., Janot, N., Regier, T. Z., Graham, D. E., … Liang, L. (2015). Geochemical drivers of organic matter decomposition in arctic tundra soils. *BIOGEOCHEMISTRY*, *126*(3), 397–414. https://doi.org/10.1007/s10533-015-0165-5

Herndon, E., AlBashaireh, A., Singer, D., Chowdhury], T. [Roy, Gu, B., & Graham, D. (2017). Influence of iron redox cycling on organo-mineral associations in Arctic tundra soil. *Geochimica et Cosmochimica Acta*, *207*, 210–231. https://doi.org/https://doi.org/10.1016/j.gca.2017.02.034

Heslop, J. K., Chandra, S., Sobzcak, W. V, Davydov, S. P., Davydova, A. I., Spektor, V. V, & Anthony, K. M. W. (2017). Variable respiration rates of incubated permafrost soil extracts from the Kolyma River lowlands, north-east Siberia. *POLAR RESEARCH*, *36*. https://doi.org/10.1080/17518369.2017.1305157

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*, *36*(2). https://doi.org/10.1029/2021GB007105

Hodgkins, S. B., Tfaily, M. M., Podgorski, D. C., McCalley, C. K., Saleska, S. R., Crill, P. M., … Cooper, W. T. (2016). Elemental composition and optical properties reveal changes in dissolved organic matter along a permafrost thaw chronosequence in a subarctic peatland. *Geochimica et Cosmochimica Acta*, *187*, 123–140. https://doi.org/10.1016/j.gca.2016.05.015

Jilkova, V., Devetter, M., Bryndova, M., Hajek, T., Kotas, P., Lulakova, P., … Macek, P. (2021). Carbon Sequestration Related to Soil Physical and Chemical Properties in the High Arctic. *GLOBAL BIOGEOCHEMICAL CYCLES*, *35*(9). https://doi.org/10.1029/2020GB006877

Kane, E. S., Chivers, M. R., Turetsky, M. R., Treat, C. C., Petersen, D. G., Waldrop, M., … McGuire, A. D. (2013). Response of anaerobic carbon cycling to water table manipulation in an Alaskan rich fen. *Soil Biology and Biochemistry*, *58*, 50–60. https://doi.org/https://doi.org/10.1016/j.soilbio.2012.10.032

Kane, E. S., Valentine, D. W., Michaelson, G. J., Fox, J. D., & Ping, C.-L. (2006). Controls over pathways of carbon efflux from soils along climate and black spruce productivity gradients in interior Alaska. *Soil Biology and Biochemistry*, *38*(6), 1438–1450. https://doi.org/https://doi.org/10.1016/j.soilbio.2005.11.004

Kane, E. S., Turetsky, M. R., Harden, J. W., McGuire, A. D., & Waddington, J. M. (2010). Seasonal ice and hydrologic controls on dissolved organic carbon and nitrogen concentrations in a boreal-rich fen. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *115*. https://doi.org/10.1029/2010JG001366

Kawahigashi, M., Prokushkin, A., & Sumida, H. (2011). Effect of fire on solute release from organic horizons under larch forest in Central Siberian permafrost terrain. *Geoderma*, *166*(1), 171–180. https://doi.org/https://doi.org/10.1016/j.geoderma.2011.07.027

Koch, J. C., Runkel, R. L., Striegl, R., & McKnight, D. M. (2013). Hydrologic controls on the transport and cycling of carbon and nitrogen in a boreal catchment underlain by continuous permafrost. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *118*(2), 698–712. https://doi.org/10.1002/jgrg.20058

Lim, A. G., Loiko, S. V, Kuzmina, D. M., Krickov, I. V, Shirokova, L. S., Kulizhsky, S. P., … Pokrovsky, O. S. (2021). Dispersed ground ice of permafrost peatlands: Potential unaccounted carbon, nutrient and metal sources. *Chemosphere*, *266*, 128953. https://doi.org/10.1016/j.chemosphere.2020.128953

Lindborg, T., Rydberg, J., Tröjbom, M., Berglund, S., Johansson, E., Löfgren, A., … Laudon, H. (2016). Biogeochemical data from terrestrial and aquatic ecosystems in a periglacial catchment, West Greenland. *Earth System Science Data*, *8*(2), 439–459. https://doi.org/10.5194/essd-8-439-2016

Littlefair, C. A., & Tank, S. E. (2018). Biodegradability of Thermokarst Carbon in a Till-Associated, Glacial Margin Landscape: The Case of the Peel Plateau, NWT, Canada. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *123*(10), 3293–3307. https://doi.org/10.1029/2018JG004461

Liu, N., Michelsen, A., & Rinnan, R. (2020). Vegetation and soil responses to added carbon and nutrients remain six years after discontinuation of long-term treatments. *Science of the Total Environment*, *722*, 137885. https://doi.org/10.1016/j.scitotenv.2020.137885

Loiko, S. V, Pokrovsky, O. S., Raudina, T. V, Lim, A., Kolesnichenko, L. G., Shirokova, L. S., … Kirpotin, S. N. (2017). Abrupt permafrost collapse enhances organic carbon, CO2, nutrient and metal release into surface waters. *Chemical Geology*, *471*, 153–165. https://doi.org/https://doi.org/10.1016/j.chemgeo.2017.10.002

MacDonald, E. N., Tank, S. E., Kokelj, S. V., Froese, D. G., & Hutchins, R. H. S. (2021). Permafrost-derived dissolved organic matter composition varies across permafrost end-members in the western Canadian Arctic. *Environmental Research Letters*, *16*(2). https://doi.org/10.1088/1748-9326/abd971

Mangal, V., DeGasparro, S., Beresford, D. V, & Guéguen, C. (2020). Linking molecular and optical properties of dissolved organic matter across a soil-water interface on Akimiski Island (Nunavut, Canada). *Science of The Total Environment*, *704*, 135415. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.135415

Masyagina, O. V, Tokareva, I. V, & Prokushkin, A. S. (2016). Post fire organic matter biodegradation in permafrost soils: Case study after experimental heating of mineral horizons. *Science of The Total Environment*, *573*, 1255–1264. https://doi.org/https://doi.org/10.1016/j.scitotenv.2016.04.195

McFarlane, K. J., Throckmorton, H. M., Heikoop, J. M., Newman, B. D., Hedgpeth, A. L., Repasch, M. N., … Wilson, C. J. (2022). Age and chemistry of dissolved organic carbon reveal enhanced leaching of ancient labile carbon at the permafrost thaw zone. *BIOGEOSCIENCES*, *19*(4), 1211–1223. https://doi.org/10.5194/bg-19-1211-2022

Mörsdorf, M. A., Baggesen, N. S., Yoccoz, N. G., Michelsen, A., Elberling, B., Ambus, P. L., & Cooper, E. J. (2019). Deepened winter snow significantly influences the availability and forms of nitrogen taken up by plants in High Arctic tundra. *Soil Biology and Biochemistry*, *135*, 222–234. https://doi.org/https://doi.org/10.1016/j.soilbio.2019.05.009

Neff, J. C., & Hooper, D. U. (2002). Vegetation and climate controls on potential CO_2, DOC and DON production in northern latitude soils. *Global Change Biology*, *8*(9), 872–884. https://doi.org/10.1046/j.1365-2486.2002.00517.x

Nielsen, C. S., Michelsen, A., Strobel, B. W., Wulff, K., Banyasz, I., & Elberling, B. (2017). Correlations between substrate availability, dissolved CH_4, and CH_4 emissions in an arctic wetland subject to warming and plant removal. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *122*(3), 645–660. https://doi.org/10.1002/2016JG003511

O'Donnell, J. A., Aiken, G. R., Butler, K. D., Guillemette, F., Podgorski, D. C., & Spencer, R. G. M. (2016). DOM composition and transformation in boreal forest soils: The effects of temperature and organic-horizon decomposition state. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *121*(10), 2727–2744. https://doi.org/10.1002/2016JG003431

O'Donnell, J. A., Turetsky, M. R., Harden, J. W., Manies, K. L., Pruett, L. E., Shetler, G., & Neff, J. C. (2009). Interactive Effects of Fire, Soil Climate, and Moss on CO_2 Fluxes in Black Spruce Ecosystems of Interior Alaska. *ECOSYSTEMS*, *12*(1), 57–72. https://doi.org/10.1007/s10021-008-9206-4

Oiffer, L., & Siciliano, S. D. (2009). Methyl mercury production and loss in Arctic soil. *Science of the Total Environment*, *407*(5), 1691–1700. https://doi.org/10.1016/j.scitotenv.2008.10.025

Olefeldt, D., & Roulet, N. T. (2012). Effects of permafrost and hydrology on the composition and transport of dissolved organic carbon in a subarctic peatland complex. *Journal of Geophysical Research: Biogeosciences*, *117*(1). https://doi.org/10.1029/2011JG001819

Olefeldt, D., & Roulet, N. T. (2014). Permafrost conditions in peatlands regulate magnitude, timing, and chemical composition of catchment dissolved organic carbon export. *Global Change Biology*, *20*(10), 3122–3136. https://doi.org/10.1111/gcb.12607

Olefeldt, D., Roulet, N. T., Bergeron, O., Crill, P., Bäckstrand, K., & Christensen, T. R. (2012). Net carbon accumulation of a high-latitude permafrost palsa mire similar to permafrost-free peatlands. *Geophysical Research Letters*. https://doi.org/10.1029/2011GL050355

Olsrud, M., & Christensen, T. R. (2011). Carbon partitioning in a wet and a semiwet subarctic mire ecosystem based on in situ ^{14}C pulse-labelling. *Soil Biology and Biochemistry*, *43*(2), 231–239. https://doi.org/10.1016/j.soilbio.2010.09.034

Pastor, A., Poblador, S., Skovsholt, L. J., & Riis, T. (2020). Microbial carbon and nitrogen processes in high-Arctic riparian soils. *PERMAFROST AND PERIGLACIAL PROCESSES*, *31*(1), 223–236. https://doi.org/10.1002/ppp.2039

Patzner, M. S., Mueller, C. W., Malusova, M., Baur, M., Nikeleit, V., Scholten, T., … Bryce, C. (2020). Iron mineral dissolution releases iron and associated organic carbon during permafrost thaw. *Nature Communications*, *11*(1), 1–11. https://doi.org/10.1038/s41467-020-20102-6

Patzner, M. S., Logan, M., McKenna, A. M., Young, R. B., Zhou, Z., Joss, H., … Bryce, C. (2022). Microbial iron cycling during palsa hillslope collapse promotes greenhouse gas emissions before complete permafrost thaw. *Communications Earth & Environment*, *3*(1), 76. https://doi.org/10.1038/s43247-022-00407-8

Payandi-Rolland, D., Shirokova, L. S., Tesfa, M., Bénézeth, P., Lim, A. G., Kuzmina, D., … Pokrovsky, O. S. (2020). Dissolved organic matter biodegradation along a hydrological continuum in permafrost peatlands. *Science of The Total Environment*, *749*, 141463. https://doi.org/10.1016/J.SCITOTENV.2020.141463

Payandi-Rolland, D., Shirokova, L. S., Labonne, F., Bénézeth, P., & Pokrovsky, O. S. (2021). Impact of freeze-thaw cycles on organic carbon and metals in waters of permafrost peatlands. *Chemosphere*, *279*, 130510. https://doi.org/10.1016/j.chemosphere.2021.130510

Payandi-Rolland, D., Shirokova, L. S., Nakhle, P., Tesfa, M., Abdou, A., Causserand, C., … Pokrovsky, O. S. (2020). Aerobic release and biodegradation of dissolved organic matter from frozen peat: Effects of temperature and heterotrophic bacteria. *CHEMICAL GEOLOGY*, *536*. https://doi.org/10.1016/j.chemgeo.2019.119448

Petersen, D. G., Blazewicz, S. J., Firestone, M., Herman, D. J., Turetsky, M., & Waldrop, M. (2012). Abundance of microbial genes associated with nitrogen cycling as indices of biogeochemical process rates across a vegetation gradient in Alaska. *Environmental Microbiology*, *14*(4), 993–1008. https://doi.org/10.1111/j.1462-2920.2011.02679.x

Pokrovsky, O. S., Reynolds, B. C., Prokushkin, A. S., Schott, J., & Viers, J. (2013). Silicon isotope variations in Central Siberian rivers during basalt weathering in permafrost-dominated larch forests. *Chemical Geology*, *355*, 103–116. https://doi.org/https://doi.org/10.1016/j.chemgeo.2013.07.016

Pokrovsky, O. S., Schott, J., Kudryavtzev, D. I., & Dupré, B. (2005). Basalt weathering in Central Siberia under permafrost conditions. *Geochimica et Cosmochimica Acta*, *69*(24), 5659–5680. https://doi.org/10.1016/j.gca.2005.07.018

Pokrovsky, O. S., Manasypov, R. M., Loiko, S. V, & Shirokova, L. S. (2016). Organic and organo-mineral colloids in discontinuous permafrost zone. *Geochimica et Cosmochimica Acta*, *188*, 1–20. https://doi.org/https://doi.org/10.1016/j.gca.2016.05.035

Poulin, B. A., Ryan, J. N., Tate, M. T., Krabbenhoft, D. P., Hines, M. E., Barkay, T., … Aiken, G. R. (2019). Geochemical Factors Controlling Dissolved Elemental Mercury and Methylmercury Formation in Alaskan Wetlands of Varying Trophic Status. *Environmental Science and Technology*, *53*(11), 6203–6213. https://doi.org/10.1021/acs.est.8b06041

Prokushkin, A. S., Gavrilenko, I. V, Abaimov, A. P., Prokushkin, S. G., & Samusenko, A. V. (2006). Dissolved organic carbon in upland forested watersheds underlain by continuous permafrost in Central Siberia. *Mitigation and Adaptation Strategies for Global Change*, *11*(1), 223–240. https://doi.org/10.1007/s11027-006-1022-6

Prokushkin, A. S., Gleixner, G., McDowell, W. H., Ruehlow, S., & Schulze, E.-D. (2007). Source- and substrate-specific export of dissolved organic matter from permafrost-dominated forested watershed in central Siberia. *GLOBAL BIOGEOCHEMICAL CYCLES*, *21*(4). https://doi.org/10.1029/2007GB002938

Prokushkin, A. S., Kajimoto, T., Prokushkin, S. G., McDowell, W. H., Abaimov, A. P., & Matsuura, Y. (2005). Climatic factors influencing fluxes of dissolved organic carbon from the forest floor in a continuous-permafrost Siberian watershed. *CANADIAN JOURNAL OF FOREST RESEARCH*, *35*(9), 2130–2140. https://doi.org/10.1139/X05-150

Rasmussen, L. H., Michelsen, A., Ladegaard-Pedersen, P., Nielsen, C. S., & Elberling, B. (2020). Arctic soil water chemistry in dry and wet tundra subject to snow addition, summer warming and herbivory simulation. *Soil Biology and Biochemistry*, *141*, 107676. https://doi.org/https://doi.org/10.1016/j.soilbio.2019.107676

Raudina, T. V, Loiko, S. V, Lim, A., Manasypov, R. M., Shirokova, L. S., Istigechev, G. I., … Pokrovsky, O. S. (2018). Permafrost thaw and climate warming may decrease the CO2, carbon, and metal concentration in peat soil waters of the Western Siberia Lowland. *Science of The Total Environment*, *634*, 1004–1023. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.04.059

Raudina, T. V, Loiko, S. V, Lim, A. G., Krickov, I. V, Shirokova, L. S., Istigechev, G. I., … Pokrovsky, O. S. (2017). Dissolved organic carbon and major and trace elements in peat porewater of sporadic, discontinuous, and continuous permafrost zones of western Siberia. *BIOGEOSCIENCES*, *14*(14), 3561–3584. https://doi.org/10.5194/bg-14-3561-2017

Ro, H.-M., Ji, Y., & Lee, B. (2018). Interactive effect of soil moisture and temperature regimes on the dynamics of soil organic carbon decomposition in a subarctic tundra soil. *GEOSCIENCES JOURNAL*, *22*(1), 121–130. https://doi.org/10.1007/s12303-017-0052-2

Roehm, C. L., Giesler, R., & Karlsson, J. (2009). Bioavailability of terrestrial organic carbon to lake bacteria: The case of a degrading subarctic permafrost mire complex. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *114*. https://doi.org/10.1029/2008JG000863

Rogers, J. A., Galy, V., Kellerman, A. M., Chanton, J. P., Zimov, N., & Spencer, R. G. M. (2021). Limited Presence of Permafrost Dissolved Organic Matter in the Kolyma River, Siberia Revealed by Ramped Oxidation. *JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES*, *126*(7). https://doi.org/10.1029/2020JG005977

Roth, V.-N., Dittmar, T., Gaupp, R., & Gleixner, G. (2013). Latitude and pH driven trends in the molecular composition of DOM across a north south transect along the Yenisei River. *Geochimica et Cosmochimica Acta*, *123*, 93–105. https://doi.org/https://doi.org/10.1016/j.gca.2013.09.002

Schostag, M., Stibal, M., Jacobsen, C. S., Baelum, J., Tas, N., Elberling, B., … Prieme, A. (2015). Distinct summer and winter bacterial communities in the active layer of Svalbard permafrost revealed by DNA- and RNA-based analyses. *FRONTIERS IN MICROBIOLOGY*, *6*. https://doi.org/10.3389/fmicb.2015.00399

Shakil, S., Tank, S. E., Kokelj, S. V., Vonk, J. E., & Zolkos, S. (2020). Particulate dominance of organic carbon mobilization from thaw slumps on the Peel Plateau, NT: Quantification and implications for stream systems and permafrost carbon release. *Environmental Research Letters*, *15*(11). https://doi.org/10.1088/1748-9326/abac36

Shatilla, N. J., & Carey, S. K. (2019). Assessing inter-annual and seasonal patterns of DOC and DOM quality across a complex alpine watershed underlain by discontinuous permafrost in Yukon, Canada. *Hydrology and Earth System Sciences*, *23*(9), 3571–3591. https://doi.org/10.5194/hess-23-3571-2019

Shirokova, L. S., Pokrovsky, O. S., Kirpotin, S. N., Desmukh, C., Pokrovsky, B. G., Audry, S., & Viers, J. (2013). Biogeochemistry of organic carbon, CO_2, CH_4, and trace elements in thermokarst water bodies in discontinuous permafrost zones of Western Siberia. *BIOGEOCHEMISTRY*, *113*(1–3), 573–593. https://doi.org/10.1007/s10533-012-9790-4

Shirokova, L. S., Bredoire, R., Rols, J.-L. L., & Pokrovsky, O. S. (2017). Moss and Peat Leachate Degradability by Heterotrophic Bacteria: The Fate of Organic Carbon and Trace Metals. *Geomicrobiology Journal*, *34*(8), 641–655. https://doi.org/10.1080/01490451.2015.1111470

Shirokova, L. S., Chupakov, A. V, Zabelina, S. A., Neverova, N. V, Payandi-Rolland, D., Causserand, C., … Pokrovsky, O. S. (2019). Humic surface waters of frozen peat bogs (permafrost zone) are highly resistant to bio- and photodegradation. *BIOGEOSCIENCES*, *16*(12), 2511–2526. https://doi.org/10.5194/bg-16-2511-2019

Shirokova, L. S., Labouret, J., Gurge, M., Gerard, E., Ivanova, I. S., Zabelina, S. A., & Pokrovsky, O. S. (2017). Impact of Cyanobacterial Associate and Heterotrophic Bacteria on Dissolved Organic Carbon and Metal in Moss and Peat Leachate: Application to Permafrost Thaw in Aquatic Environments. *AQUATIC GEOCHEMISTRY*, *23*(5–6), 331–358. https://doi.org/10.1007/s10498-017-9325-7

Sistla, S. A., Schaeffer, S., & Schimel, J. P. (2019). Plant community regulates decomposer response to freezing more strongly than the rate or extent of the freezing regime. *ECOSPHERE*, *10*(2). https://doi.org/10.1002/ecs2.2608

Speetjens, N. J., Tanski, G., Martin, V., Wagner, J., Richter, A., Hugelius, G., … Vonk, J. E. (2022). Dissolved organic matter characterization in soils and streams in a small coastal low-arctic catchment. *Biogeosciences*, *19*(July), 3073–3097. Retrieved from https://doi.org/10.5194/bg-19-3073-2022

Stutter, M. I., & Billett, M. F. (2003). Biogeochemical controls on streamwater and soil solution chemistry in a High Arctic environment. *Geoderma*, *113*(1), 127–146. https://doi.org/https://doi.org/10.1016/S0016-7061(02)00335-X

Takano, S., Yamashita, Y., Tei, S., Liang, M., Shingubara, R., Morozumi, T., … Sugimoto, A. (2021). Stable Water Isotope Assessment of Tundra Wetland Hydrology as a Potential Source of Arctic Riverine Dissolved Organic Carbon in the Indigirka River Lowland, Northeastern Siberia. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.699365

Tanski, G., Couture, N., Lantuit, H., Eulenburg, A., & Fritz, M. (2016). Eroding permafrost coasts release low amounts of dissolved organic carbon (DOC) from ground ice into the nearshore zone of the Arctic Ocean. *Global Biogeochemical Cycles*, *30*(7), 1054–1068. https://doi.org/10.1002/ 2015GB005337

Tanski, G., Lantuit, H., Ruttor, S., Knoblauch, C., Radosavljevic, B., Strauss, J., … Fritz, M. (2017). Transformation of terrestrial organic matter along thermokarst-affected permafrost coasts in the Arctic. *Science of the Total Environment*, *581–582*, 434–447. https://doi.org/10.1016/j.scitotenv.2016.12.152

Textor, S. R., Wickland, K. P., Podgorski, D. C., Johnston, S. E., & Spencer, R. G. M. (2019). Dissolved Organic Carbon Turnover in Permafrost-Influenced Watersheds of Interior Alaska: Molecular Insights and the Priming Effect. *FRONTIERS IN EARTH SCIENCE*, *7*. https://doi.org/10.3389/feart.2019.00275

Thompson, M. S., Giesler, R., Karlsson, J., & Klaminder, J. (2015). Size and characteristics of the DOC pool in near-surface subarctic mire permafrost as a potential source for nearby freshwaters. *Arctic, Antarctic, and Alpine Research*, *47*(1), 49–58. https://doi.org/10.1657/AAAR0014-010

Treat, C. C., Wollheim, W. M., Varner, R. K., & Bowden, W. B. (2016). Longer thaw seasons increase nitrogen availability for leaching during fall in tundra soils. *ENVIRONMENTAL RESEARCH LETTERS*, *11*(6). https://doi.org/10.1088/1748-9326/11/6/064013

Trusiak, A., Treibergs, L. A., Kling, G. W., & Cory, R. M. (2018). The role of iron and reactive oxygen species in the production of CO_2 in arctic soil waters. *GEOCHIMICA ET COSMOCHIMICA ACTA*, *224*, 80–95. https://doi.org/10.1016/j.gca.2017.12.022

Voigt, C., Lamprecht, R. E., Marushchak, M. E., Lind, S. E., Novakovskiy, A., Aurela, M., … Biasi, C. (2017). Warming of subarctic tundra increases emissions of all three important greenhouse gases – carbon dioxide, methane, and nitrous oxide. *Global Change Biology*, *23*(8), 3121–3138. https://doi.org/10.1111/gcb.13563

Voigt, C., Marushchak, M. E., Mastepanov, M., Lamprecht, R. E., Christensen, T. R., Dorodnikov, M., … Biasi, C. (2019). Ecosystem carbon response of an Arctic peatland to simulated permafrost thaw. *Global Change Biology*, *25*(5), 1746–1764. https://doi.org/10.1111/gcb.14574

Voigt, C., Marushchak, M. E., Lamprecht, R. E., Jackowicz-Korczyński, M., Lindgren, A., Mastepanov, M., … Biasi, C. (2017). Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(24), 6238–6243. Retrieved from https://www.jstor.org/stable/26484198

Vonk, J. E., Mann, P. J., Dowdy, K. L., Davydova, A., Davydov, S. P., Zimov, N., … Holmes, R. M. (2013). Dissolved organic carbon loss from Yedoma permafrost amplified by ice wedge thaw. *ENVIRONMENTAL RESEARCH LETTERS*, *8*(3). https://doi.org/10.1088/1748-9326/8/3/035023

Vonk, J. E., Mann, P. J., Davydov, S., Davydova, A., Spencer, R. G. M., Schade, J., … Holmes, R. M. (2013). High biolability of ancient permafrost carbon upon thaw. *GEOPHYSICAL RESEARCH LETTERS*, *40*(11), 2689–2693. https://doi.org/10.1002/grl.50348

Waldrop, M. P., Harden, J. W., Turetsky, M. R., Petersen, D. G., McGuire, A. D., Briones, M. J. I., … Pruett, L. E. (2012). Bacterial and enchytraeid abundance accelerate soil carbon turnover along a lowland vegetation gradient in interior Alaska. *Soil Biology and Biochemistry*, *50*, 188–198. https://doi.org/https://doi.org/10.1016/j.soilbio.2012.02.032

Waldrop, M. P., & Harden, J. W. (2008). Interactive effects of wildfire and permafrost on microbial communities and soil processes in an Alaskan black spruce forest. *GLOBAL CHANGE BIOLOGY*, *14*(11), 2591–2602. https://doi.org/10.1111/j.1365-2486.2008.01661.x

Ward, C. P., & Cory, R. M. (2015). Chemical composition of dissolved organic matter draining permafrost soils. *Geochimica et Cosmochimica Acta*, *167*, 63–79. https://doi.org/https://doi.org/10.1016/j.gca.2015.07.001

Ward, C. P., Nalven, S. G., Crump, B. C., Kling, G. W., & Cory, R. M. (2017). Photochemical alteration of organic carbon draining permafrost soils shifts microbial metabolic pathways and stimulates respiration. *NATURE COMMUNICATIONS*, *8*. https://doi.org/10.1038/s41467-017-00759-2

Whittinghill, K. A., Finlay, J. C., & Hobbie, S. E. (2014). Bioavailability of dissolved organic carbon across a hillslope chronosequence in the Kuparuk River region, Alaska. *Soil Biology and Biochemistry*, *79*, 25–33. https://doi.org/https://doi.org/10.1016/j.soilbio.2014.08.020

Wickland, K. P., Neff, J. C., & Aiken, G. R. (2007). Dissolved organic carbon in Alaskan boreal forest: Sources, chemical characteristics, and biodegradability. *ECOSYSTEMS*, *10*(8), 1323–1340. https://doi.org/10.1007/s10021-007-9101-4

Wickland, K. P., Waldrop, M. P., Aiken, G. R., Koch, J. C., Jorgenson, Mt., & Striegl, R. G. (2018). Dissolved organic carbon and nitrogen release from boreal Holocene permafrost and seasonally frozen soils of Alaska. *ENVIRONMENTAL RESEARCH LETTERS*, *13*(6). https://doi.org/10.1088/1748-9326/aac4ad

Yun, J., Jung, J. Y., Kwon, M. J., Seo, J., Nam, S., Lee, Y. K., & Kang, H. (2022). Temporal Variations Rather than Long-Term Warming Control Extracellular Enzyme Activities and Microbial Community Structures in the High Arctic Soil. *MICROBIAL ECOLOGY*, *84*(1), 168–181. https://doi.org/10.1007/s00248-021-01859-9

Zolkos, S., & Tank, S. E. (2019). *Permafrost geochemistry and retrogressive thaw slump morphology (Peel Plateau, Canada), v. 1.0 (2017-2017).* https://doi.org/10.5885/45573XD-28DD57D553F14BF0