Review article: Terrestrial dissolved organic carbon in northern permafrost

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Field Code Changed

Abstract

As the permafrost region warms and permafrost soils thaw, vast 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. Across permafrost zones the highest median 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. However, median DOC concentrations varied in these zones across ecosystem type, with ~~The~~the highest median DOC concentrations in each ecosystem type 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 median 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). 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 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 also 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, laterally transport the greatest quantities of DOC, and represent the store of 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 are important drivers of DOC ~~cocnentrations~~ concentrations (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.

Previous studies have highlighted that the 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. 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. 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., 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.

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 ecosystems associated with the highest DOC concentrations, and thus ecosystems with the greatest potential for DOC mobilization.

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). ~~We used the same search query string as above to search for 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,	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.*

	letter, editorial, case report, or reflection?	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 (%), soil carbon:nitrogen (C:N), 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 soil C:N have been shown to be a good proxy for decomposition (Biester et al., 2014), where high C:N values indicate higher decomposition has previously occurred. 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 (Table S1) 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 lens, 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 l~~L~~ens 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 we used Kruskal-Wallis analysis to test for differences in median DOC concentrations among the various study regions and areas that included 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, data was first transformed using a Box Cox transformation and the optimal λ using the *MASS* package (Ripley et al., 2019). We then 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) when assessing the relationship of DOC concentrations with continuous and categorical variables. We performed this analysis to determine how the drivers of DOC concentrations across ecosystems 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;

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

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 as ± the interquartile range, 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~~Table S2) across the northern circumpolar permafrost region. All studies except, for one (Olefeldt et al., 2012), reported DOC concentrations.

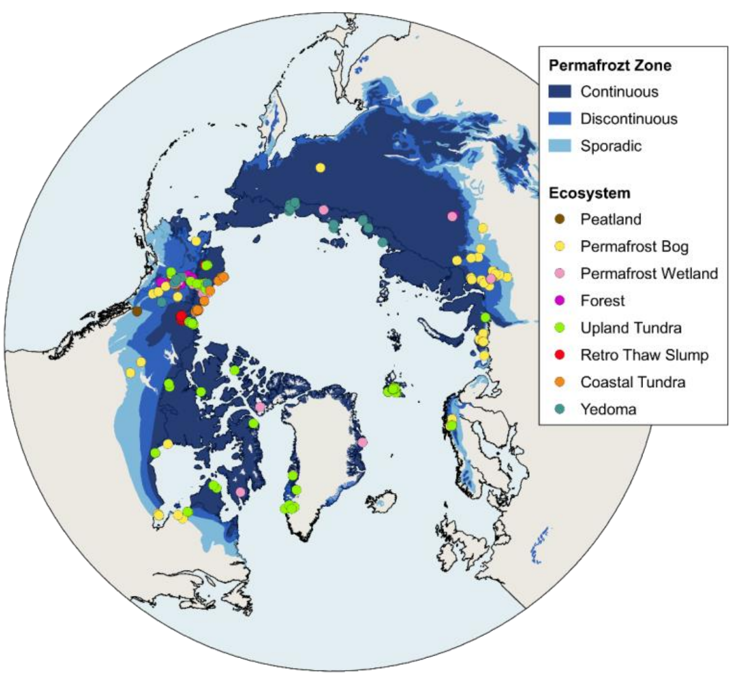

Figure 1. Map of sampling locations where DOC measurements (n=562) from the top 3 m for each ecosystem type. In many cases, the same sampling location was used in multiple studies leading to some overlap, therefore the number of sampling sites included in the data set (562) are not all clearly identifiable 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.

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}. 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}). The lowest median of 33 ± 77 mg L^{-1} 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}) and Sub-Arctic Boreal (n = 442; 58 ± 97 mg L^{-1}) ecoregions, and lowest in the Arctic Tundra (n = 1,209; 25 ± 75 mg L^{-1}) and Sub-Arctic Tundra (n = 493; 43 ± 61 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}) and Histel soils (n = 935; 53 ± 72 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}) and Turbels (n = 820; 31 ± 62 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}), 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}) and the permafrost lens (n = 729; 30 ± 113 mg L^{-1}).

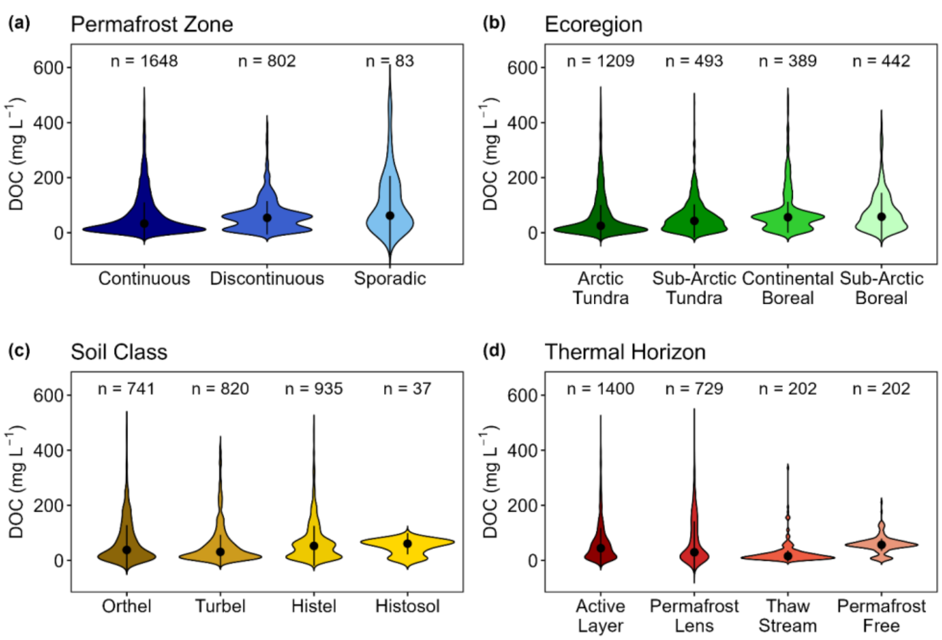

Figure 2. Violin plots of DOC concentrations (mg L^{-1}) found in the top 3 m across (a) permafrost zones, (b) ecoregions, (c) soil classes, and (d) thermal horizons. (a) Dark to light blue shading represents the permafrost zones Continuous, Discontinuous, and Sporadic, according to Brown et al., (1997). (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). (d) Dark to light red shading represents the thermal horizons Active Layer, Permafrost Lens, Thaw Stream, and Permafrost Free. 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 S1). Permafrost bogs, upland tundra, and permafrost wetlands were the most represented in the database with regards to DOC concentrations (~~Table S1~~Table S2). The majority of permafrost bog measurements came from studies with field sites within Canada (Figure 1; ~~Table S1~~Table S2), 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 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 DOC concentrations from 9 studies, ~~Table S1~~Table S2). 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}) and permafrost bogs (63 ± 75 mg L^{-1}) ecosystems. The lowest DOC concentrations were found in permafrost wetlands (7 ± 20 mg L^{-1}) and Yedoma ecosystems (9 ± 18 mg L^{-1}), both of which had only slightly lower median DOC concentrations than retrogressive thaw slumps (15 ± 21 mg L^{-1}).

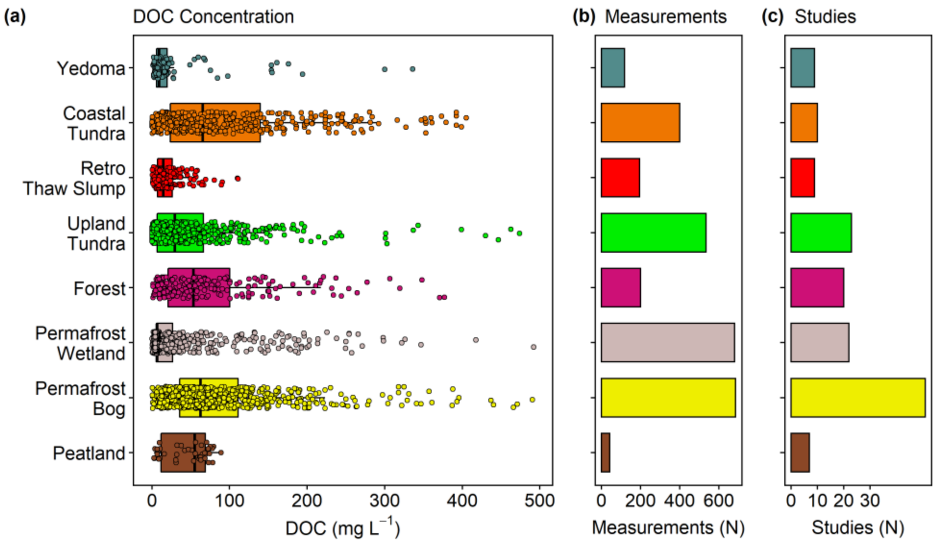

Figure 3. Boxplot and jitter plot of (a) DOC concentrations (mg L^{-1}), (b) the number of DOC measurements, and (c) number of studies including DOC measurements were taken from the top 3 m for each ecosystem type. Retro Thaw Slump = Retrogressive Thaw Slump. Boxes represents the interquartile range (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}) and permafrost bogs (n = 248; 78 ± 144 mg L^{-1}) sites, and lowest found in Yedoma sites (n = 91; 8 ± 10 mg L^{-1}). The highest active layer DOC concentrations were in permafrost bogs (n =

276; 64 ± 61 mg L^{-1}) and forest (n = 185; 57 ± 84 mg L^{-1}) sites, and lowest found in permafrost wetland sites (n = 274; 10 ± 42 mg L^{-1}).

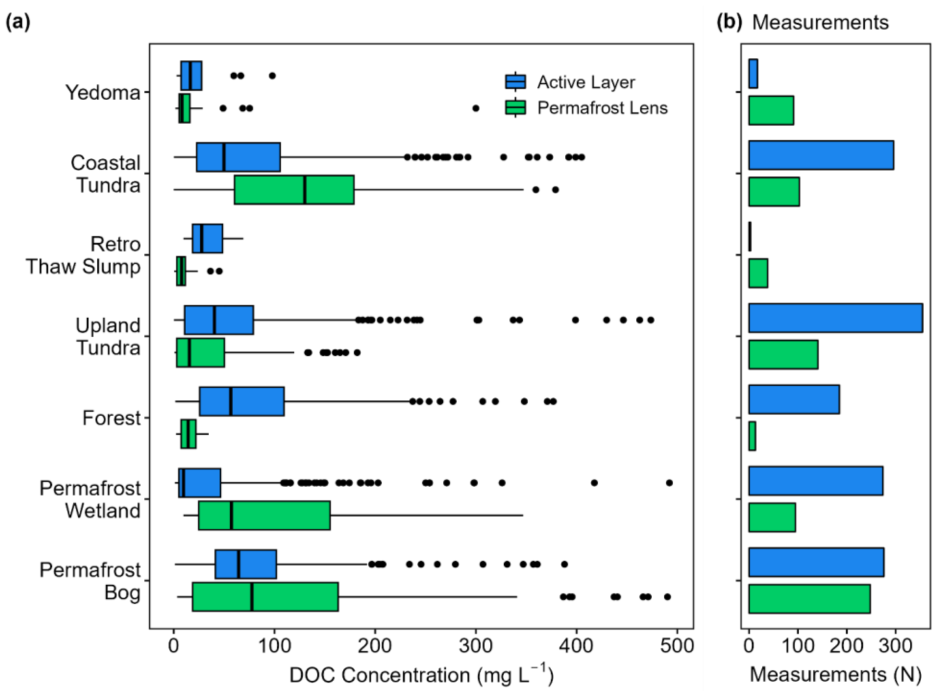

Figure 4 . Boxplot of (a) DOC concentrations (mg L^{-1}) and (b) the number of DOC measurements in the Active Layer and Permafrost Lens thermal horizons of each ecosystem type. Only DOC concentrations from ecosystems with these thermal horizons present is used, thus no permafrost-free sites are included. 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~~Table S3, 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~~Table S3). Similarly, the highest DOC concentrations using these two most common filter sizes were highest in permafrost bog and coastal tundra ecosystems (~~Table S3~~Table S4). 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~~Table S5, ~~S5~~S6). 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~~Table S5) and ecosystems (~~Table S5~~Table S6) 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~~Table S7) and ecosystems (~~Table S7~~Table S8), thus comparison of all three methods is not complete. Trends in DOC measured using the combustion and persulphate method (~~Table S6~~Table S7, S~~7~~) 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.

3.5 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 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 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 relationship with DOC concentrations were total dissolved nitrogen content (mg L^{-1}) and C:N ratios, respectively (Figure 5b). The positive relationship of DOC 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 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.

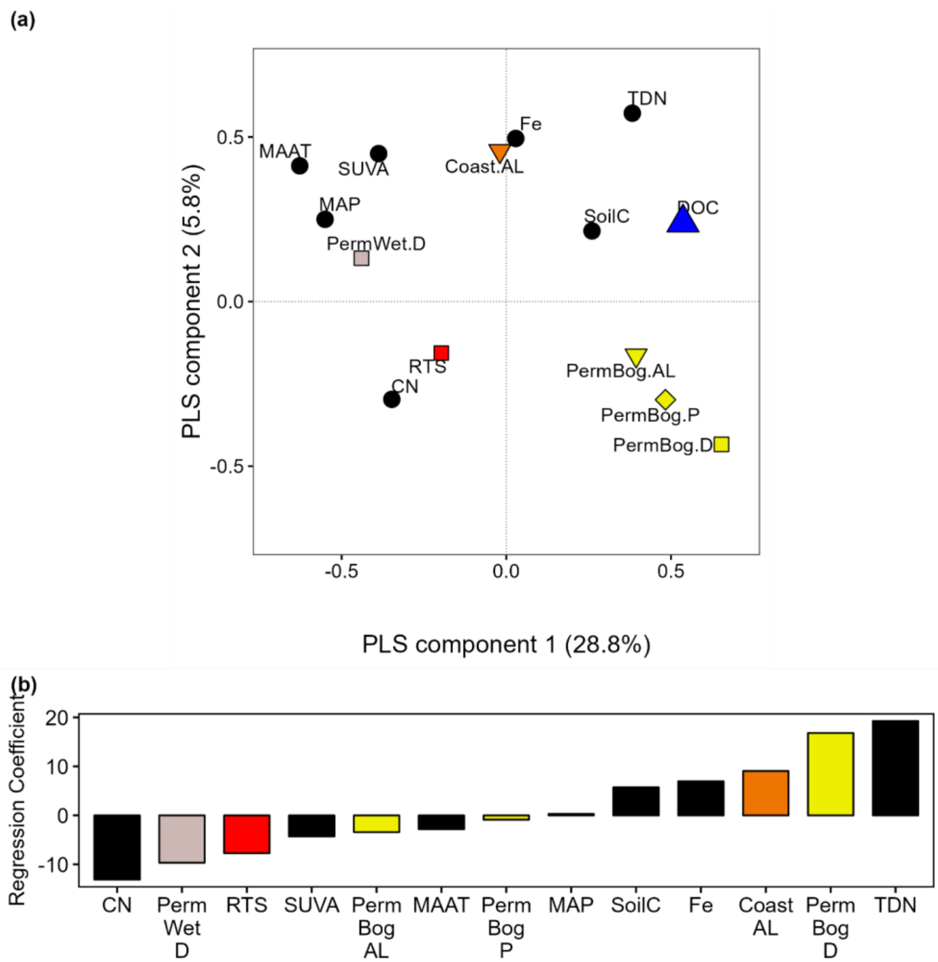

Figure 5. Partial least squares regression (PLS) (a) loadings plot explaining 37% of the variability observed in DOC concentrations. (b) Bar plot of PLS regression coefficients showing the relative importance of each variable in predicting DOC concentrations. Regression coefficients on y-axis are normalized 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. 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. PermBog.AL = active layer of permafrost bog ecosystem class and is yellow. PermBog.P = permafrost lens of permafrost bog ecosystem class and is yellow\. PermBog.D = disturbed permafrost bog ecosystem class and is yellow.

3.6 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}) and coastal tundra ecosystems (n = 427; 72 ± 126 mg L^{-1}; 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}). 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}), whereas the lowest were found in sites that had experienced active layer detachment (n = 6; 4 ± 2 mg L^{-1}). Pristine sites had the highest DOC concentrations in both Yedoma (n = 114; 11 ± 15 mg L^{-1}) and forest (n = 189; 49 ± 64 mg L^{-1}) ecosystems. However, in permafrost wetland ecosystems pristine sites had the lowest DOC concentrations (n = 766; 7 ± 51 mg L^{-1}) with sites that were affected by both thermokarst wetland formation (n = 17; 21 ± 26 mg L^{-1}) and active layer thickening (n = 12; 41 ± 13 mg L^{-1}) 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 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 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.

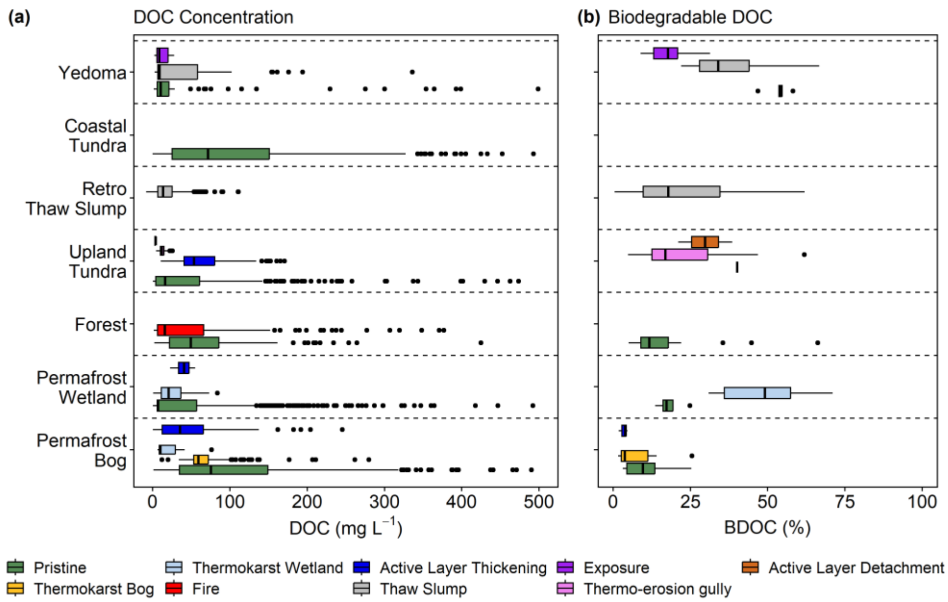

Figure 6. DOC concentrations (mg L^{-1}) and biodegradable DOC (BDOC; %) from the top 3 m following disturbance including data from both field based and incubation studies. (a) DOC concentrations from each ecosystem type following disturbance where data was available. (b) Biodegradable DOC (BDOC) from 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.

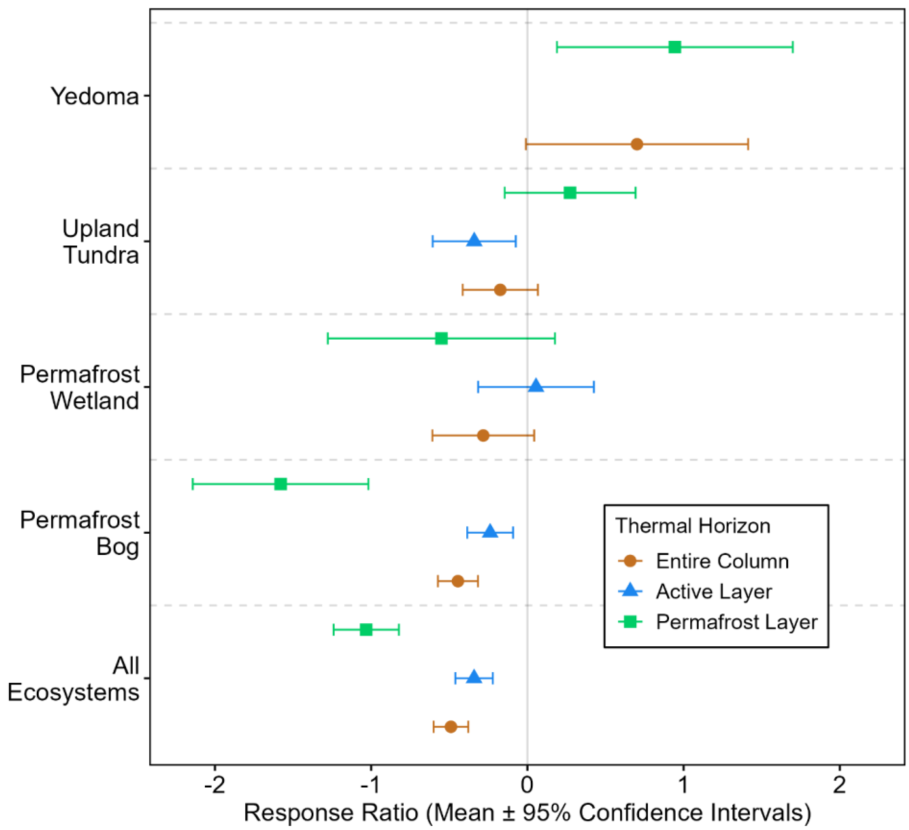

Figure 7. Response ratios of DOC concentrations from the top 3 m following thermokarst formation (calculated using Eq. 1). Response ratio means allow for relative comparison of changes in DOC following thermokarst formation between different ecosystem types. Negative values indicate lower DOC concentrations 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 DOC concentrations in the 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 Variation in DOC across ecosystems

The accumulation of high DOC concentrations we show in 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 a 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, 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.

Coastal tundra ecosystems had similarly high DOC concentrations to those found in permafrost bogs (Figure 3a). Coastal tundra ecosystems represented the highest concentrations of DOC in mineral permafrost soils, with the highest concentrations found in 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 (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 remaining ecosystems characterised by mineral soils with an upper organic layer, i.e., forests, upland tundra, and Yedoma. 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 upland tundra ecosystems were found to negatively correlate with DOC concentrations (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). 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-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).

4.3 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.. 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). 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 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~~Table S2). 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). 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 three different filter sizes, eleven different extraction procedures, and four 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 is freely and publicly available at https://doi.org/10.17043/heffernan-2024-doc-1

~~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.

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