First Pan-Arctic Assessment of Dissolved Organic Carbon in Permafrost-Region Lakes

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Abstract. Lakes in permafrost regions are dynamic landscape components and play an important role for climate change feedbacks. Lake processes such as mineralization and flocculation of dissolved organic carbon (DOC), one of the main carbon fractions in lakes, contribute to the greenhouse effect and are part of the global carbon cycle. These processes are in focus of climate research but studies so far are limited to specific study regions. In our synthesis, we analysed 2,167 water samples from 1,833 lakes across the Arctic in permafrost regions of Alaska, Canada, Greenland, and Siberia to provide first pan-Arctic insights for linkages between DOC concentrations and the environment. Using published data and unpublished datasets from the author team we report regional DOC differences linked to latitude, permafrost zones, ecoregions, geology, near-surface soil organic carbon contents, and ground ice classification of each lake region. The lake DOC concentrations in our dataset range from 0 mg L^{-1} to 1,130 mg L^{-1} (10.8 mg L^{-1} median DOC concentration). Regarding the permafrost regions of our synthesis, we found median lake DOC concentrations of 12.4 mg L^{-1} (Siberia), 12.3 mg L^{-1} (Alaska), 10.3 mg L^{-1} (Greenland), and 4.5 mg L^{-1} (Canada). Our synthesis shows a significant relationship of lake DOC concentration and ecoregion of the lake. We found higher lake DOC concentrations in boreal permafrost sites compared to tundra sites. About 22 % of the lakes in our extensive dataset are located in regions with ice-rich syngenetic permafrost deposits (yedoma). Yedoma contains large amounts of easily erodible organic carbon and we found significantly higher DOC concentrations in yedoma lakes compared to non-yedoma lakes. Compared to previous studies we found a weak significant relationship of soil organic carbon content and lake DOC concentration as well as between ground-ice content and lake DOC. Our pan-Arctic dataset shows that the DOC concentration of a lake strongly depends on its environmental properties, especially on permafrost extent and ecoregion, as

well as vegetation, which is the most important driver of lake DOC in this study. This new dataset will be fundamental to quantify a pan-Arctic lake DOC pool for estimations of the impact of lake DOC on the global carbon cycle and climate change.

1 Introduction

In northern high latitudes, where mean annual ground temperatures are below 0 °C, permafrost has been an important carbon

5   sink for thousands of years since freezing is one of the most effective mechanisms for long-term carbon fixation in soils (Schuur et al., 2008; Grosse et al., 2011). Permafrost landscapes store large amounts (~1,300-1,600 Pg C) of soil organic carbon (Hugelius et al., 2014) and are a potential source for carbon emissions to the atmosphere when soil temperatures exceed 0° C and permafrost thaws (McGuire et al., 2009; Koven et al., 2011). Through anthropogenic/recent climate change, Arctic permafrost regions experienced an increase of permafrost temperatures by 0.5° to 2° C and a local deepening of the active

10   layer of up to 90 cm since the 1970s (Romanovsky et al., 2010; IPCC, 2013; Biskaborn et al., 2019). More recently, permafrost regions warmed globally by an average of 0.29° +/- 0.12° C over the 2007-2016 period, with some of the strongest warming trend (about 0.9° C per decade) measured in individual boreholes in Siberia (Biskaborn et al., 2019). In addition, thermokarst and thermo-erosion processes act as a mechanism for the rapid release of permafrost carbon in the climate system (Walter Anthony et al., 2018; Turetsky et al., 2020). Hence, the impact of global climate change on permafrost regions and their carbon

15   cycling has to be thoroughly investigated.

Of particular interest is ice-rich permafrost, which is vulnerable to rapid degradation processes, such as thermokarst and thermo-erosion that lead to ground ice melt, subsequent soil volume loss, and ground subsidence. Consequently, characteristic landforms such as thermo-erosional valleys, thaw slumps, and thermokarst lakes form in these regions. Thermokarst lakes are quite dynamic and widespread landscape features in the Arctic (Jones et al., 2011; Grosse et al., 2013; Manasypov et al., 2015),

20   and their biochemical processes play an important role for carbon cycling and climate change feedbacks in the Arctic and beyond (Walter Anthony et al., 2018).

In lakes, dissolved organic carbon (DOC) is one of the main carbon fractions (Tranvik et al., 2009). DOC in lakes can be produced in the lake itself (autochthonuous DOC) or in the catchment of the lake (allochthonuous DOC) (Sobek et al., 2007). The organic carbon content of terrestrial soils is the main source for allochthonuous DOC. Because DOC is mobile and can be

25   chemically labile (Vonk et al., 2013a, b), large amounts of DOC are transported into lakes, where they can be either stored in lake sediments due to flocculation (Tranvik et al., 2009) or mineralized by photo oxidation or microbial activity, resulting in emission of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere (Frey & Smith, 2005; Battin et al., 2008; Tranvik et al., 2009; Vonk et al., 2013a, b). This lake-based process is a major component of the global carbon cycle and contributes to the greenhouse effect (Finlay et al., 2006). Vonk et al. (2015) suggested that this form of carbon flux represents roughly one

30   third to one-half of the net carbon exchange from land to the atmosphere in the Arctic.

Numerous studies estimated organic carbon pools in Arctic soils (Zimov et al., 2006; Strauss et al., 2013; Hugelius et al., 2014, Hugelius et al., 2020) while others investigated DOC and its release from northern high latitude soils and ground ice (Freeman

et al., 2004; Wickland et al., 2007; Prokushkin et al., 2009; Fritz et al., 2015; Tanski et al., 2016). The export of riverine DOC has also been frequently investigated in the High Arctic (Semkin et al., 2005; Raymond et al., 2007; Holmes et al., 2012, Frey et al., 2016; Fouché et al., 2017; Coch et al., 2019), the Low Arctic (Coch et al., 2018), and Subarctic regions (Carey, 2003; Laudon et al., 2004; Petrone et al., 2006). While high-latitude rivers usually have a pronounced seasonal DOC concentration
5   peak during snowmelt (Finlay et al., 2006), this river-borne DOC was found to be utilized rapidly by microbes (Spencer et al., 2015). For example, incubation studies at the Kolyma River in Siberia indicated a DOC loss of 50 % in less than seven days (Spencer et al., 2015). Additionally, DOC concentration in rivers appears to be linked to mean annual temperature in which highest DOC concentrations were found in areas ranging between 0° and 3° C mean annual air temperature (Laudon et al., 2012).

10   In recent years, DOC concentrations, lability and mobility in arctic lake systems, including thermokarst lakes, have been investigated; however, these studies have largely been limited to specific regions. For example, it was found that hydrologic linkages between a pond and its catchment affect the load of DOC in ponds in northern Siberia (Abnizova et al., 2014), and that DOC in different lake-basin types responds differently to climate change (Larsen et al., 2017). For specific regions of West Siberia, Shirokova et al. (2013) found a negative correlation between DOC concentration and the size and age of
15   thermokarst lakes. Among global lakes (7500 lakes from 35 land-cover types), Sobek et al. (2007) found no correlation between lake area or other lake properties and DOC concentration, but DOC concentration in lakes was found to depend on catchment properties such as topography and climate. However, permafrost-region lakes, which represent approximately 25 % of global lakes (Lehner & Döll, 2004), only comprised about 10 % of the 7,500 global lakes studied with respect to DOC. Hence, a pan-Arctic focused analysis of the spatial variability of lake DOC in permafrost regions is still missing.

20   The objectives of this study are to synthesize existing datasets of lake DOC in northern permafrost regions, to provide first insights for linkages between DOC concentration and environmental parameters (permafrost zone, ecoregion, deposit types, ground ice content and soil organic carbon content), and to identify drivers for lake DOC concentration in this region affected by rapid climate change. Our synthesis includes published datasets as well as unpublished datasets from the author team to find regional differences in DOC concentration of lakes across the Arctic.

2 Study areas

   In our synthesis, we included 2,167 samples from 1,833 lakes of 13 study areas (22 sites) across the Arctic, sampled from year 1979 to 2017 (Table 1). Lakes in our study are located from 59.2° to 82.5° northern latitude. 49.3 % of our dataset come from sites in Alaska, 24.2 % from Canada, 23.3 % from Siberia and 3.2 % from Greenland. All study lakes are located in landscapes influenced by permafrost (Fig. 1). Lakes in this synthesis cover the full range of permafrost extents from continuous,
30   discontinuous, isolated, and sporadic permafrost areas.

   Study sites of the North and Northwest Alaska study area (Fig. 1, 1-3) are predominantly located in the continuous permafrost zone (82 % of the lakes studied in this area) and are dominated by tundra climate and very cold subarctic climate.

46 % of the studied lakes in this study area are located in the tundra ecoregion and 54 % in the tundra-boreal transition region. The North and Northwest Alaska study area is mainly composed of fluvial and yedoma deposits (62 %). The Southcentral Alaska study area (Fig. 1, 4) is predominantly underlain by discontinuous permafrost and characterized by very cold subarctic to tundra climate. Studied lakes in this study area are located in the boreal ecoregion and are surrounded by glacio-moraine (67 %) and mountain-alluvium (13 %) deposits. The study sites in the Interior Alaska study area (Fig. 1, 5-6) are predominantly located in the discontinuous permafrost zone (65 %), 19 % of studied lakes in this study area are located in the isolated permafrost zone, belonging to the Denali National Park and Preserve (Fig. 1, 5). The Interior Alaska study area is affected by very cold subarctic to tundra climate and is situated in the boreal zone. This area is mainly underlain by fluvial (55 %) and yedoma (16 %) deposits.

The study sites in the Yukon and Northwest Territories study areas (Fig. 1, 7-10) are predominantly situated in the continuous permafrost zone (65 % of studied lakes in this area), the discontinuous permafrost zone (30 %), and some lakes in the sporadic permafrost zone (5 %), located in the Whitehorse transect.
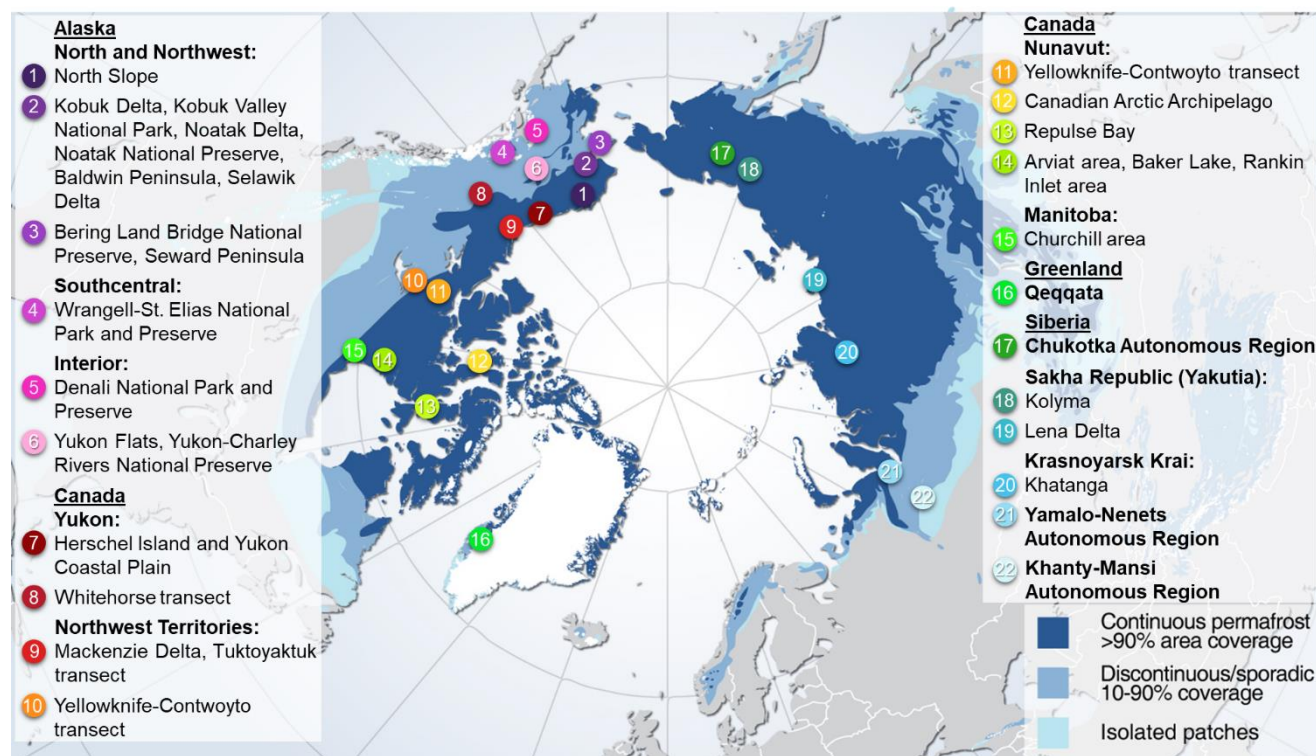
Figure 1: Overview of study regions (underlined bold font), study areas (bold font) and sites overlain of the map of permafrost zones (Background map: after Brown et al., 1997).

Studied lakes of this study area are mainly affected by very cold subarctic climate and can be found in the tundra ecoregion, in the boreal-tundra transition zone and in the boreal forest, with glacial deposits. Study sites in the Nunavut study area (Fig. 1, 11-14) are located in the zone of continuous permafrost and are characterized by cool continental to very-cold subarctic climate. Studied lakes in this area are situated in the tundra ecoregion and are surrounded by glacial, bedrock and colluvial

5 deposits. Studied lakes of the Manitoba study area (Fig. 1, 15) are located in the continuous permafrost zone and are affected by very cold subarctic climate. This study area is predominantly situated in the boreal forest and is underlain by glacio-marine deposits.

The Qeqqata study area (Fig. 1, 16) in Greenland is situated in the continuous permafrost zone and is affected by Arctic climate. Studied lakes in this area are located in the tundra ecoregion and surrounded by aeolian deposits.

10 The Siberian Yamalo-Nenets Autonomous Region (A.R.) study area (Fig. 1, 21) covers the continuous, discontinuous and sporadic permafrost zones and is affected by subarctic climate.

Table 1: Summary of DOC sample size and regional lake distribution.

	Study area	Months of sample collection	Years of sample collection
Greenland	Qeqqata	June – August	2002, 2003, 2009, 2013, 2014
Siberia	Yamalo-Nenets Autonomous Region	June - August	1999-2001, 2010, 2011, 2013, 2015, 2016
	Khanty-Mansi Autonomous Region	July - August	1999-2001, 2016
	Chukotka Autonomous Region	July	2016
	Krasnoyarsk Krai	July - August	2013
	Sakha Republic (Yakutia)	July - October	2002, 2013, 2014, 2016
Canada	Yukon	July	1990, 2014-2016
	Northwest Territories	July, September	1990, 1991, 2004
	Nunavut	June - September	1979, 1980, 1983-1985, 1989-1997, 1999, 2006-2010, 2017
	Manitoba	July - August	2006-2010
Alaska	North and Northwest	June - September	2008, 2009, 2011-2016
	Southcentral	May - September	2009-2011, 2015, 2016
	Interior	May - September	2003-2008, 2010-2012, 2014-2016

Here, 72 % of the studied lakes are situated in boreal forest and 28 % in the tundra ecoregion, especially on the Yamal Peninsula. The Yamalo-Nenets A.R. study area is underlain by glacial-morain, glacio-lacustrine, glacio-fluvial and alluvial deposits. Studied lakes of the Khanty-Mansi A.R. study area (Fig. 1, 22) are situated in the continuous and isolated permafrost zone and are affected by subarctic to tundra climate. This area is situated in the boreal forest and dominated by glacio-fluvial

5 deposits. The Chukotka A.R. study area (Fig. 1, 17) is situated in the continuous permafrost zone and is characterized by subarctic to tundra climate. Studied lakes in this study area cover the full range of tundra ecoregion, boreal forest and tundra-boreal transition region, and are surrounded by ice-rich syngenetic permafrost deposits (yedoma) and fluvial deposits. The Khatanga study site in the Krasnoyarsk Krai study area (Fig. 1, 20) is located in the continuous permafrost zone and is characterized by subarctic climate. This area is situated in the tundra ecoregion and underlain by lacustrine, alluvial and eluvial

10 deposits. The Sakha Republic (Yakutia) study area (Fig. 1, 18-19) includes sites in the Lena River Delta (Kurungnakh Island, Sobo-Sise Island, Samoylov Island, and Bykovsky Peninsula) and sites close to the Kolyma River. These sites are situated in the continuous permafrost zone and are affected by very cold subarctic climate. The Lena Delta study site is situated in the tundra ecoregion, whereas the Kolyma study site is situated in the boreal forest. The study lakes of the Sakha Republic study area are mainly located in ice-rich syngenetic permafrost deposits (yedoma), or fluvial and alluvial deposits.

3 Methods

3.1 Data extraction from existing studies

For this synthesis, we searched the scientific literature for the keywords DOC and lakes in permafrost regions and largely focused on local to regional lake DOC syntheses that provided data at the individual lake level (i.e., not averaged values for groups of lakes or regions). From identified references (Pienitz et al., 1997a,b; Hamilton et al., 2001; Lim et al., 2001; Kokelj

20 et al., 2005; Medeiros et al., 2012; Halm & Griffith, 2014; Manasypov et al., 2014; Manasypov et al., 2015; Northington & Saros, 2016; Larsen et al., 2017; Osburn et al., 2017; Coch et al., 2019; Serikova et al., 2019; Johnston et al., 2020) data for 1,757 DOC samples, collected from 1,478 individual lakes, were extracted into a database for further analysis. Unpublished field data of the author team was included in the database (410 samples from 355 lakes). The database includes samples that have been collected during the period of late May to early October (Table 1). If there was a lake sampled once in a month for

25 more than one year, we calculated the average lake DOC concentration. Across our synthesis dataset, various well-established methods (Bauer & Bianchi, 2011) were used to quantify DOC concentration, including high-temperature catalytic combustion, low-temperature chemical oxidation, and photochemical oxidation. The 246 samples from Alfred-Wegener-Institute (AWI), Helmholtz Centre for Polar and Marine Research, were analysed with high-temperature catalytic combustion (Appendix A).

3.2 Sample database and geospatial analysis

30 We created a geospatial database of permafrost-region lakes with DOC data (PeRL-DOCv1) in the desktop Geoinformation System (GIS) ArcMap (10.4.1, ESRI) containing all 1,833 lakes as point features. Additional data layers were included in the

PeRL-DOC GIS for the analysis of lake environmental characteristics, including layers on permafrost and ground ice distribution (Jorgenson et al., 2008), surface geology (Jorgenson et al., 2008), and yedoma distribution (Strauss et al., 2016). For all lakes, a range of parameters (Table A1) was extracted and exported into the spreadsheet database for further analysis. For the determination of yedoma and non-yedoma areas, we used the Database of Ice-Rich Yedoma Permafrost (IRYP) by
5   Strauss et al. (2016). By using the study site descriptions from the synthesized lake DOC literature and a map of terrestrial ecoregions (Olson et al., 2004), we assigned an ecoregion for each data point.

For inferring lake genesis, each data point was assigned a deposit type, which refers to the surrounding deposit type of each lake. For this, we used the Permafrost characteristics of Alaska map by Jorgenson et al. (2008) for Alaska, Nielsen (2010) for Greenland, the Map of the Quaternary Formations of the Russian Federation (Petrov et al., 2014), the Geological Survey of
10   Canada map of Fulton (1995) for Canada, and the yedoma distribution database of IRYP (Strauss et al., 2016). Furthermore, we added the ice content for the surrounding area of each lake, using the term 'low', 'moderate', 'high' and 'variable' (Jorgenson et al., 2008; IPA permafrost map). Finally, we used the NCSCDv2 to add the soil organic carbon content of the area surrounding each lake for the upper 0 to 100 cm, 100 to 200 cm, 200 to 300 cm, and aggregated for the upper 300 cm of soil (Hugelius et al., 2014).

15   **3.3 Statistical Analysis**

To conduct statistical tests, we used RStudio (version 1.0.153). Normality was tested using the Shapiro–Wilk normality test. Because the data does not follow a normal distribution, we used the Spearman rank correlation coefficient (ρ) to measure the relationship between two variables and the Wilcoxon-Mann-Whitney test to determine the difference in means between two populations.

20   **4 Results**

4.1 Temporal variability of DOC concentration

For only 81 of 1,833 lakes in our dataset we had multi-temporal data, which means that these lakes were sampled at least two times during the ice-free period. 23 of these lakes were sampled at least two times a year in more than one year. 12 of the 81 lakes were sampled three times in a year and 17 lakes were sampled four times in a year. In total, the multi-temporal data
25   subset includes 266 samples. 44 % of these samples were collected in the post-snow melt period from April to June. The DOC concentration in this period ranged from 0 mg L^{-1} to 160.6 mg L^{-1}, with a median of 12.7 mg L^{-1}. 27 % of the samples were collected in the summer period from July to August. For these, the DOC concentration ranged from 0 mg L^{-1} to 67 mg L^{-1}, with a median of 5.4 mg L^{-1}. 29 % of the samples were collected during fall from September to October. Here, the DOC concentration ranged from 3.1 mg L^{-1} to 144.2 mg L^{-1}, with a median of 14.6 mg L^{-1}.

30   For 42 % of the multi-temporal subset we found increasing DOC concentrations in a year, regarding the variation of sub annual samples. For 42 % of the multi-temporal subset we found decreasing DOC concentrations. For 6 % of the multi-temporal

subset we found fluctuating values in sub-annual samples. In some cases, the DOC concentration increased after snowmelt and further decreased until fall or decreased in summer and increased until fall.

Overall, the multi-temporal subset is very small and these results should be treated with care due to the low sample numbers.

4.2 Variable DOC concentrations across the Arctic

5   Lakes in our database from sites across the Arctic, covering different permafrost zones, ecoregions and deposit types, show a high variation of lake DOC concentration. We found differences between the four regions of Alaska, Canada, Greenland and Siberia, as well as between study areas and study sites within these regions (Table A2). The median DOC concentration across the entire dataset was 10.8 mg L^{-1}. The concentration ranged from 0 mg L^{-1} to 1,130 mg L^{-1} (Table 2). 91.8 % of the lakes included in our dataset have a DOC concentration between 0 and 30 mg L^{-1}. Comparing DOC concentrations of lake water in

10   permafrost regions of Alaska, Canada, Greenland and Siberia, we found median DOC concentrations of 12.3 mg L^{-1}, 4.2 mg L^{-1}, 10.3 mg L^{-1} and 12.4 mg L^{-1}, respectively.

Table 2: DOC concentrations according to study sites.

	Study area	No. of samples/ No. of lakes	DOC concentration [mg L^{-1}]		
			range	mean	median
Greenland	Qeqqata	81/59	1-61.3	18.5	10.3
Siberia	Yamalo-Nenets A.R.	249/249	3.2-63.4	18.1	15.6
	Khanty-Mansi A.R.	41/41	5.8-36.1	13.7	11
	Chukotka A.R.	20/20	1.1-19.6	9.5	9.6
	Krasnoyarsk Krai	32/32	2.3-19.4	8.3	8.3
	Sakha Republic (Yakutia)	127/85	2.4-33.3	9.6	9.8
Canada	Yukon	54/54	3.1-38.7	15.4	14.7
	Northwest Territories	79/79	1.7-30	10.2	9.1
	Nunavut	302/294	0-31.9	3.9	2.9
	Manitoba	17/17	2.7-21.2	9.1	7
Alaska	North and Northwest	499/397	0-53.3	9.6	8.6
	Southcentral	138/126	0.8-36.8	14.1	13.8
	Interior	528/380	1.4-1,130	25	16.8
	Total	2,167/1,833	0-1,130	14.3	10.8
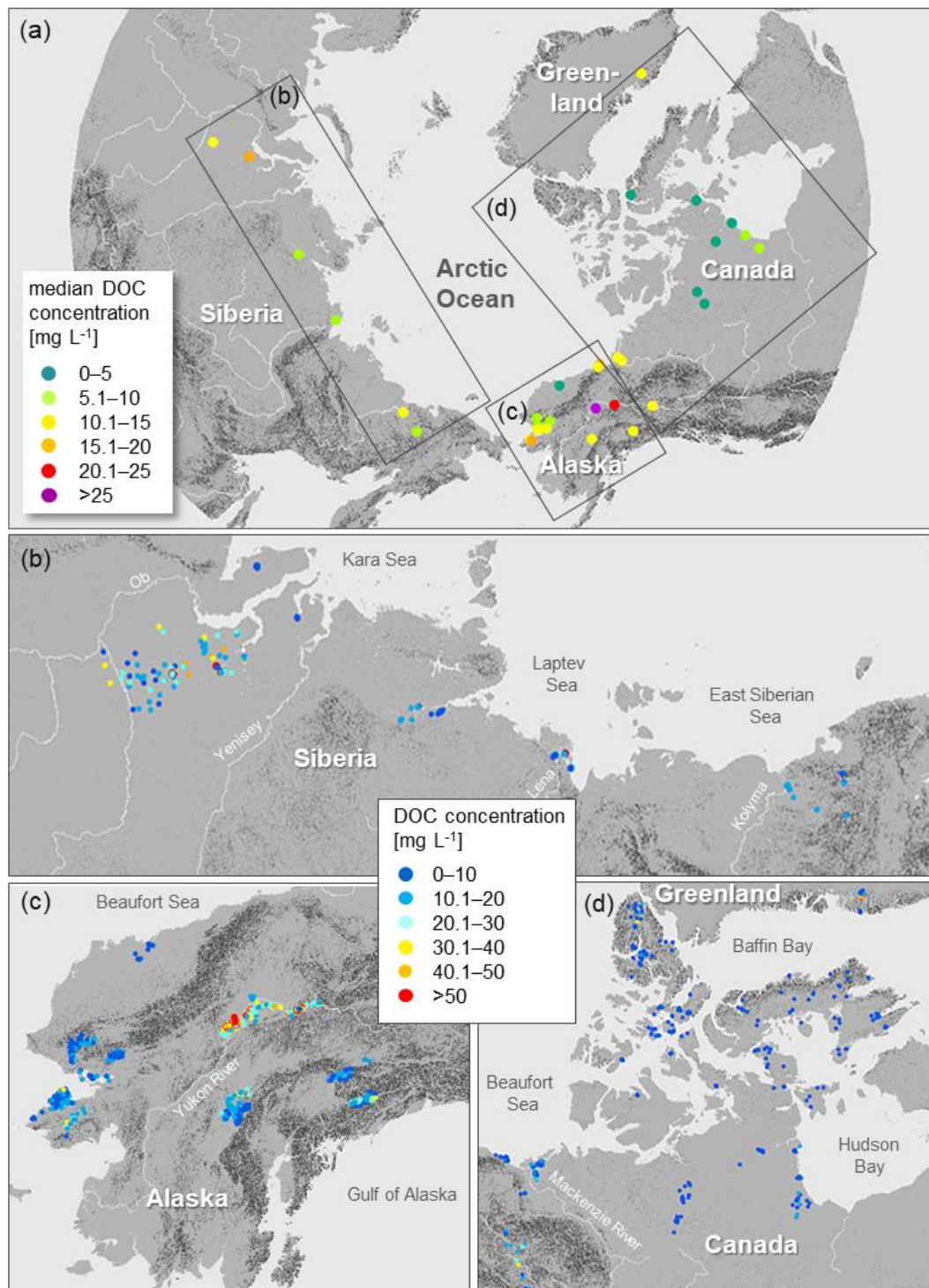
Figure 2: Map of lake DOC concentrations (mg L^{-1}) and regional variability. Median DOC concentration for each study site (a). DOC concentrations of individual lakes in the study regions Siberia (b), Alaska (c) and Canada and Greenland (d) (Background map: ESRI).

Figure 2a highlights the variability of median DOC concentration in the permafrost regions of Alaska, Canada, Greenland and Siberia, and demonstrates the large range of DOC concentration in Alaska. In contrast, lakes in the Canadian permafrost region had a smaller range of DOC concentrations (Fig. 2d). We found that 80.3 % of samples collected in Canadian lakes had a lower DOC concentration than the dataset median of 10.8 mg L^{-1}. In Alaska and Siberia, we found that about 58 % of the lakes

5   had higher DOC concentrations than the dataset median.

Lakes in Greenland showed a 50:50 ratio with DOC concentration below and above the dataset median. A large number of lakes with DOC concentration above 30 mg L^{-1} were found in Interior Alaska in the Yukon Flats and Yukon-Charley Rivers National Preserve (Fig. 2c). We had four lakes with strikingly high DOC concentrations more than ten times higher than the dataset median. These concentrations are 1,130 mg L^{-1}, 507 mg L^{-1}, 433 mg L^{-1} and 173 mg L^{-1} and all four lakes were located

10   in the Yukon Flats in Interior Alaska. In addition, about 25 % of lakes with a DOC concentration above 30 mg L^{-1} were located in the Yamalo-Nenets A.R. (Fig. 2b). We found that lake DOC concentration was negatively correlated with geographic latitude of a lake (ρ = -0.3; $p < 0.05$; Table 3). The DOC concentration of lakes in the southernmost study sites (Yukon Flats and Yukon-Charley Rivers National Preserve) showed a large range from 10.2 to 1,300 mg L^{-1}, and 5.0 to 66.7 mg L^{-1}, respectively (Table A2).

15   **4.3 Higher DOC concentrations in boreal forest lakes**

In our dataset, 43.7 % of the lakes were located in the boreal forest ecoregion, 42.6 % in the tundra region, and 13.7 % in a boreal-tundra transition zone. We found a significant relationship between lake DOC concentration and the lake surrounding ecoregion (ρ = 0.31; $p < 0.05$; Table 3), with significantly lower DOC concentrations in lakes of the tundra region ($p < 0.05$). The DOC concentration of lakes in the boreal zone ranged from 0.8 mg L^{-1} to 1,130 mg L^{-1} and the median DOC concentration

20   in the boreal zone was 15.3 mg L^{-1}, whereas the DOC concentration of lakes in the tundra zone ranged from 0 mg L^{-1} to 816 mg L^{-1} with a median of 6.8 mg L^{-1} (Fig. 3).

With a median DOC concentration of 8.5 mg L^{-1}, lakes in the boreal-tundra transition zone had significantly lower DOC concentrations than lakes in the boreal forest ($p < 0.05$).

4.4 Lower DOC concentrations in lakes of the continuous permafrost zone

25   Median DOC concentration were highest in lakes of the sporadic permafrost zone (17.3 mg L^{-1}) and were negatively correlated with permafrost extent (ρ = 0.37; $p < 0.05$; Fig. 3; Table 3). DOC concentrations in lakes of the discontinuous zone were significantly higher (14 mg L^{-1}) than lakes in the continuous permafrost zone (8 mg L^{-1}).

4.5 Higher lake DOC concentrations in yedoma regions

About 16 % of the 1,833 lakes of our dataset were located in regions with ice-rich syngenetic permafrost deposits (yedoma).

30   The DOC concentrations in lakes of these regions ranged from 1.7 mg L^{-1} to 50.6 mg L^{-1} with a median of 11.8 mg L^{-1}.
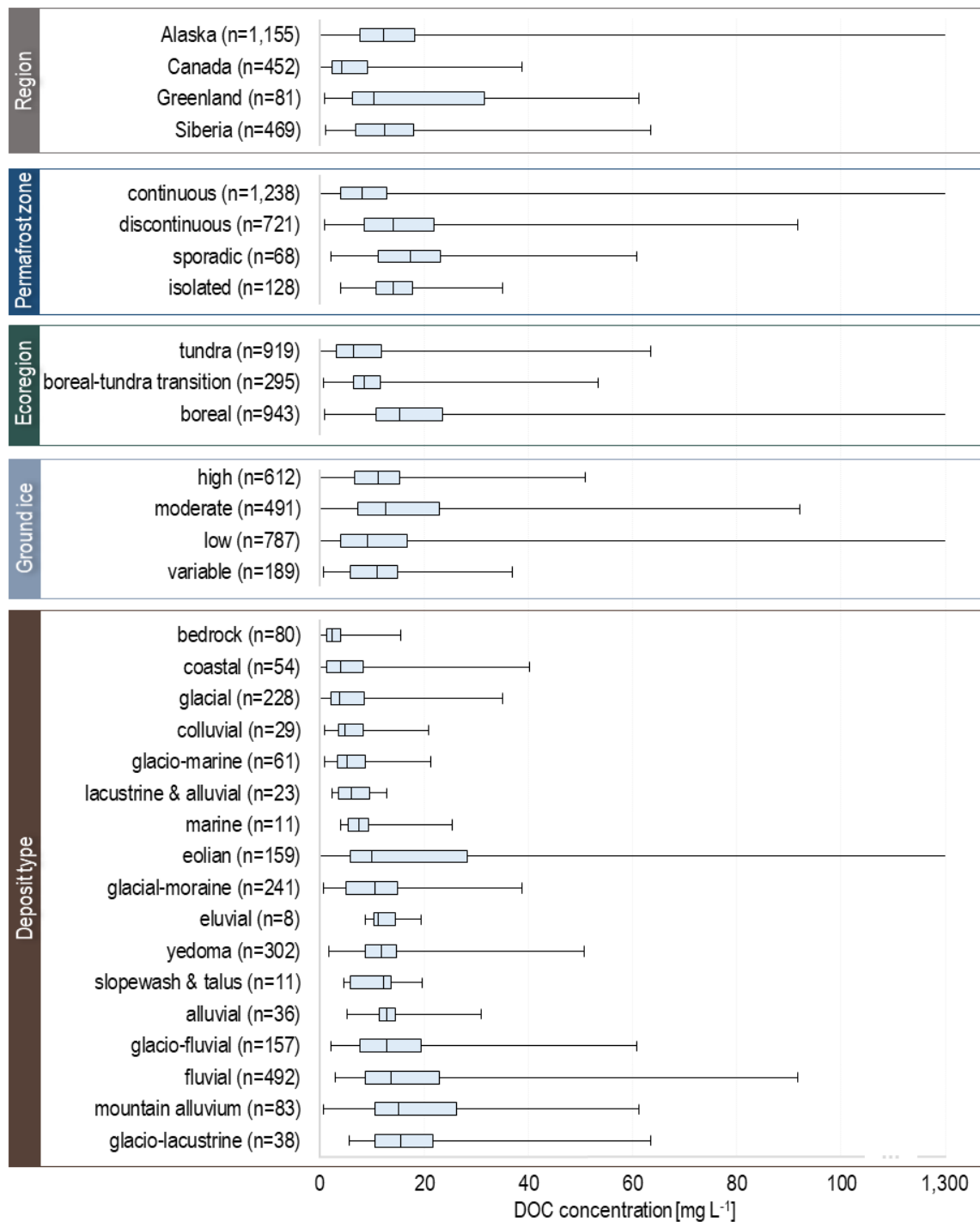
Figure 3: Dissolved Organic Carbon (DOC) concentration (mg L^{-1}) of lakes in different Arctic regions, permafrost zones, ecoregions, ground ice content, and deposit types. Note that the x-axis is interrupted between 100 mg L^{-1} and 1,300 mg L^{-1} to visually capture the wide range of the DOC concentrations.

The DOC concentrations in non-yedoma region lakes, comprising 79 % of the dataset, ranged from 0 mg L^{-1} to 1,130 mg L^{-1} and the median DOC concentration was 10.3 mg L^{-1} which is significantly lower than in the yedoma region ($p < 0.05$). Our analysis shows a weak significant relationship of the lake surrounding deposit type and lake DOC concentration ($\rho = -0.2$; $p < 0.05$; Table 3). Highest median DOC concentrations occur in lakes of areas with mountain alluvium and glacio-lacustrine deposits (15.2 mg L^{-1}, 15.5 mg L^{-1}). Lowest median DOC concentrations were found in lakes in areas underlain by bedrock, coastal and glacial deposits (2.6 mg L^{-1}, 4 mg L^{-1} and 4 mg L^{-1}).

4.6 Lower DOC concentrations in regions with low ground ice content

Lakes of our dataset were located in regions of low, moderate, high and variable ground ice content (percentage of lakes: 36.5 %, 22.8 %, 25.4 % and 8.8 %, respectively). We found a weakly positive relationship between ground ice content and lake DOC concentrations ($\rho = 0.05$; $p < 0.05$; Table 3). In regions of low ground ice content, the median amounts to 9.6 mg L^{-1}, compared to regions of moderate and high ground ice content with median DOC concentrations of 12.7 mg L^{-1} and 11.4 mg L^{-1}, respectively.

4.7 Lake DOC and Soil Organic Carbon Content (SOCC)

We analysed the relationship between lake DOC concentrations and lake surrounding SOCC and found a weakly significant relationship for SOCC of the upper 100 cm ($\rho = 0.1$; $p < 0.05$; Table 3). The significance of the relationship was getting weaker for SOCC in the upper 300 cm ($\rho = 0.09$; $p < 0.05$; Table 3).

Table 3: Results of the Spearman Rank correlation, testing the relationship between lake DOC concentration and lake parameters.

	latitude	permafrost zone	ecoregion	ground ice content	deposit type	SOCC 0-300 cm	SOCC 0-100 cm
ρ	-0.3	0.37	0.31	0.05	-0.2	0.09	0.12
p	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

5 Discussion

5.1 Ecoregion zonation as key factor for pan-Arctic lake DOC

Our study shows the strongest significant relationships between lake DOC concentration and permafrost extent, ecoregion, and geographic latitude ($\rho = 0.31$; $\rho = 0.37$; $\rho = -0.3$). In contrast to other studies conducted at a smaller spatial scale (e.g. Harms et al., 2016; Larsen et al., 2017) we found only a weak connection of lake DOC and surrounding SOCC. Our study provides an insight of potential sources of DOC in pan-Arctic lakes. We found that particular lakes in the boreal forest have higher DOC concentrations compared to tundra region lakes (Fig. 3). Soils of boreal forests are rich in organic material and

microbial degradation is low (Sobek et al. 2007). In areas of boreal forest, the frost-free period is extended and the surface water can be in contact with soil carbon for a longer time resulting in higher DOC concentrations in boreal lakes. Previous studies confirm that vegetation is an important driver for DOC in permafrost catchments (Harms et al., 2016; Coch et al., 2019). Coch et al. (2019) found higher DOC concentrations in moss and plant rich Low Arctic catchment on Herschel Island

5 in Northwest Canada compared to a High Arctic catchment at Cape Bounty, Northeast Canada. In our database we found high lake DOC concentrations in the boreal forest regions of Interior Alaska which are dominated by white and black spruce (Halm & Griffith, 2014). In contrast, higher permafrost extent in higher geographical latitudes results in lower vegetation density and further in lower DOC concentrations. For rivers and streams, Raymond and Saiers (2010) also defined organic matter from plant litter and soils as main source of DOC.

10 Changes in the structure of an ecosystem and biogeochemical fluxes due to lake DOC concentrations are affected by climate change (Sobek et al., 2005). This in turn, influences CO_2 emissions from these lakes and causes a positive feedback. With our first pan-Arctic assessment, we can confirm that the permafrost region lake DOC is largely driven by ecoregion zonation and soils, which in turn are affected by climate and topography (Sobek et al. 2007).

5.2 Pan-Arctic lakes in a global view of lake DOC

15 The median DOC concentration of our dataset (10.8 mg L^{-1}) is almost three times higher than the value (3.88 mg L^{-1}) found by Toming et al. (2020), who studied global lakes with a surface are larger than 0.1 km^2. Our study across the Arctic shows a high variation of lake DOC concentration. Canada and Greenland had the lowest median DOC concentration with low inter-site variation (Fig. 3) compared to the high variability observed in Alaska and Siberia. Whereas the Canadian and Greenlandic regions were affected by past glaciation, the majority of the Alaskan and Siberian sites were not glaciated and are characterized

20 by extensive low-lying wetlands. Our results show that lakes in areas with yedoma deposits have significantly higher DOC concentrations, which can be attributed to old labile yedoma carbon mobilized by thermos-erosion along rapidly expanding lake shores. Sepulveda-Jauregui et al. (2015) also found a higher DOC content in yedoma lakes, analysing CO_2 emissions from 40 lakes of a north-south transect in Alaska covering all permafrost types. We assume that yedoma lake generation is influencing yedoma lake DOC. Due to deep thermokarst subsidence yedoma lakes are more likely to be closed basins and not

25 connected resulting in higher DOC concentrations. In contrast, well-mixed larger and shallower lakes, where photodegradation plays an important role, are associated with lower lake DOC concentration. However, to determine the DOC source in yedoma lakes radiocarbon dating of each sample would be necessary.

While we showed that lake DOC concentration is influenced by permafrost extent and type of ecoregion they do not explain all of the variability in the dataset. Additional factors are regulating DOC. For example, air temperature, precipitation and solar

30 radiance have an influence on surface water DOC concentration (Cole et al., 2002; Molot et al., 2005; Anderson & Stedmon, 2007). Anderson & Stedmon (2007) analysed lakes in low Arctic Greenland and found highest lake DOC concentrations in areas of low precipitation and low discharge. In those areas, evaporation is high leading to higher DOC concentrations. For

our database, this connection may explain the relatively high DOC concentrations of lakes in the Yukon basin, which is very arid and evaporation can concentrate DOC.

While we found that lake latitude is correlated to lake DOC concentration, we did not investigate lake altitude. Sobek et al. (2007) and Toming et al. (2020) found for their global lake databases that lake altitude is one of the most important indicator
5   for lake DOC regarding catchment properties, with lake DOC concentrations being lowest in areas of high elevation.

5.3 Challenges of a pan-Arctic DOC assessment

Our synthesis shows a wide range of DOC concentrations in Arctic permafrost region lakes. An important uncertainty factor for analysing lake DOC concentration in a pan-Arctic context is the still very limited amount of lake DOC data compared to the very large number of lakes. This region hosts the most lake-rich landscapes on Earth (Lehner & Döll, 2004) and their
10 geologic and hydrologic origins are diverse (Pienitz et al., 2008; Vincent & Laybourne-Parry, 2008) but often connected to paleogeographic and cryosphere processes that are differing substantially from the world's other lake regions (Smith et al., 2007). The remoteness of many lakes in the Arctic results in multiple challenges to spatially and temporally representative sampling. For example, multi-temporal sampling of Arctic lakes is still very rare and limits our insights in the seasonal and long-term dynamic of lake DOC of many Arctic lake types. Further uncertainties result from still rather coarse-resolution
15 environmental data layers for the pan-Arctic such as permafrost, ground ice content, soil organic carbon, ecoregion, as well as the sparseness of high-resolution climate data. New remote sensing and numerical modelling-driven approaches to create spatially homogeneous datasets for this large region may provide a much better base for future analyses of lake DOC and its correlation with environmental factors. For example, pan-Arctic remote sensing of permafrost region disturbances (Nitze et al., 2018) may allow correlation of lake DOC data with the processes of rapid permafrost degradation, or global studies of
20 remotely sensed lake abundance and change (Pekel et al., 2016) may help to understand the dynamical aspects of lake DOC. To quantify the permafrost region lake DOC pool, an assessment of the volume of the diverse lake types in the Arctic is needed.

6 Conclusion

DOC is one of the main carbon fractions in lakes contributing to the greenhouse effect as part of the global carbon cycle. This first pan-Arctic assessment provides linkages between DOC concentrations and the environment of 1,833 lakes in permafrost
25 regions of Alaska, Canada, Greenland and Siberia. Our study compares DOC concentrations of lakes in the permafrost region with different permafrost extent, tundra and boreal-forest ecoregions, regions of different deposit types, areas with high, moderate, low and variable ground ice content and different soil organic carbon contents in the upper 3 m. In these areas, we found a wide range of DOC concentrations from 0 to 1,300 mg L^{-1} with the highest concentrations in the Yukon Flats in Interior Alaska and lowest in the North Slope in Arctic Alaska and the Canadian Arctic Archipelago. We identified a significant
30 relationship of lake DOC and the ecoregion and we found increasing lake DOC with increasing vegetation from tundra to boreal forest and decreasing latitude and permafrost extent. We conclude that ecoregion zonation is the most important driver

for lake DOC concentration in the pan-Arctic region. The new PerL-DOC database will be useful for quantification of carbon pools and fluxes from freshwater bodies across the Arctic. Our study of the pan-Arctic assessment of lake DOC concentration in permafrost regions provides a first overview of the connections between lake DOC and lake environment and provides a basis for further detailed analysis.

5 **Appendix A: DOC analysis at Alfred-Wegener-Institute (AWI)**

For DOC analysis of 246 samples collected by authors from AWI, 20 ml of the sample was filtered through a 0.7 µm pore size glass fiber filter, preserved with 20-50 µl of 30 % hydrochloric acid (HCl) and sent to AWI in Potsdam, Germany, for laboratory processing. We then treated the samples with high-temperature catalytic combustion. For the quality control during the measurement and validation of the results, standard samples with known concentrations of DOC and blank samples of

10 ultrapure water were added to the sample set. The direct method or so-called NPOC-method (Non-Purgeable-Organic-Carbon) was used to determine the DOC concentration. We filled 9 mL of the sample into a 9 mL glass vial, sealed each vial with an aluminium foil, and placed them in the vial rack of 'Shimadzu TOC-VCPH'. During measurement, the samples were acidified with hydrochloric acid to a pH value of 2-3 and afterwards treated with oxygen gas, which eliminated inorganic carbon by conversion to CO_2. In the next step, NPOC passes the catalyst, where it heats up to 680 °C and the CO_2 passes the NDIR

15 detector (Non Dispersed InfraRed). The NDIR detector measures the concentration and related software calculates the average of up to five measurement procedures of each sample (Manual Shimadzu/TOC-V, 2008). The DOC concentration was recorded in mg L^{-1}.

Table A1: Parameters for lake analyses.

General	Lake Name/ID	
	Sample date	
	Location	Latitude and Longitude.
	Study Area	Qeqqata, Yamalo-Nenets Autonomous Okrug, Khanty-Mansi Autonomous Okrug, Chukotka Autonomous Okrug, Krasnoyarsk Krai, Sakha Republic (Yakutia), Yukon Territory, Northwest-Territories, Nunavut, Manitoba, North and Northwest Alaska, Southcentral Alaska, Interior Alaska.
	Study Site	Qeqqata, Yamalo-Nenets Autonomous Okrug, Khanty-Mansi Autonomous Okrug, Chukotka Autonomous Okrug, Khatanga, Lena Delta, Kolyma, Herschel Island, Yukon Coastal Plain, Whitehorse transect, Mackenzie Delta, Tuktoyaktuk transect, Yellowknife-

		Contwoyto transect (Northwest-Territories), Yellowknife-Contwoyto transect (Nunavut), Canadian Arctic Archipelago, Repulse Bay, Arviat area, Baker Lake area, Rankin Inlet area, Churchill area, North Slope, Kobuk Delta, Kobuk Valley national Park, Noatak Delta, Noatak National Preserve, Baldwin Peninsula, Selawik Delta, Bering Land Bridge National Preserve, Seward Peninsula, Wrangell-St. Elias National Park and Preserve, Denali National Park and Preserve, Yukon Flats, Yukon-Charley Rivers National Preserve.
	Permafrost zone	Continuous, Discontinuous, Isolated, Sporadic.
	Ecoregion	Tundra, Boreal Forest (Olson et al., 2004, link: https://databasin.org/datasets/ 68635d7c77f1475f9b6c1d1dbe0a4c4c).
	Data Source	Reference or sample collector.
Hydrochemistry	DOC	In mg L^{-1}.
Geology	Deposits	Coastal, eolian, yedoma, glacial-moraine, glacio-lacustrine, glacio-fluvial, fluvial, mountain alluvium, glacio-marine, glacial, bedrock, colluvial, alluvial, lacustrine and alluvial, marine, eluvial, slopewash.
	Ice Content	Low, moderate, high, variable.
	Soil Organic Carbon Content	Kg C m^{-2}, in 0 – 100 cm, 100 – 200 cm, 200 – 300 cm, and summed 0 – 300 cm of upper soil.
Geomorphology	Lake surface area	In ha, if available.
	Lake perimeter	In km, if available.

Table A2: DOC concentrations in study sites.

Study area	Study site	n samples / n lakes	DOC concentration [mg L^{-1}] range	mean	median
Alaska		**1,165/903**	**0 – 1,130**	**17**	**12.3**
North and		*499/397*	*0 – 53.3*	*9.6*	*8.6*
Northwest	North Slope	64/16	0 – 20.8	3	1.7
	Kobuk Delta	14/14	4.3 – 40.1	11.2	8.1
	Kobuk Valley National Park	157/112	2.9 – 53.3	9.7	7.9
	Noatak Delta	3/3	7.9 – 12.2	9.8	9.3

		Noatak National Preserve	114/107	0.7 – 20.9	9.6	9.2
		Baldwin Peninsula	3/3	12.6 – 35.4	20.3	12.8
		Selawik Delta	4/4	8.4 – 11.4	10.4	11
		Bering Land Bridge National Preserve	121/119	4.7 – 25.8	11.2	10.7
		Seward Peninsula	19/19	1.4 – 38.3	16.1	16.4
	Southcentral	*Wrangell-St. Elias National Park and Preserve*	*138/126*	*0.8 – 36.8*	*14.1*	*13.8*
	Interior		*528/380*	*1.4 – 1,130*	*25*	*16.8*
		Denali National Park and Preserve	257/161	1.4 - 35	12.6	12.4
		Yukon Flats	150/140	10.2 – 1,130	48.7	30.3
		Yukon-Charley Rivers National Preserve	121/79	5 – 66.7	23.8	22.7
Canada			**452/444**	**0 – 38.7**	**6.6**	**4.2**
	Yukon		*54/54*	*3.1 – 38.7*	*15.4*	*14.7*
	Territory	Herschel Island	20/20	5.4 – 38.7	17.6	17.3
		Yukon Coastal Plain	12/12	5.6 – 25.4	14.6	12.7
		Whitehorse transect	22/22	3.1 – 35.1	13.9	12.9
	Northwest-		*79/79*	*1.7 - 30*	*10.2*	*9.1*
	Territories	Mackenzie Delta	22/22	6.8 - 30	13.4	13
		Tuktoyaktuk transect	37/37	3.9 – 29.9	11.3	10.1
		Yellowknife-Contwoyto transect	20/20	1.7 – 9.1	4.7	4.3
	Nunavut		*302/294*	*0 – 31.9*	*3.9*	*2.9*
		Yellowknife-Contwoyto transect	4/4	1.6 – 2.7	2.2	2.3
		Canadian Arctic Archipelago	220/212	0 – 31.9	3.6	2.5
		Repulse Bay	6/6	2 – 5.4	3.8	4.2
		Arviat area	25/25	2.6 – 11.7	6.5	5.8
		Baker Lake area	28/28	2.2 – 5.4	3.2	3.1
		Rankin Inlet area	19/19	2.7 – 17.4	5.9	4.5
	Manitoba	*Churchill area*	*17/17*	*2.7 – 21.2*	*9.1*	*7*
Greenland	**Qeqqata**		**81/59**	**1 – 61.3**	**18.5**	**10.3**

Siberia			**469/427**	**1.1 – 63.4**	**14.4**	**12.4**
Yamalo-Nenets Autonomous Region			*249/249*	*3.2 – 63.4*	*18.1*	*15.6*
Khanty-Mansi Autonomous Region			*41/41*	*5.8 – 36.1*	*13.7*	*11*
Chukotka Autonomous Region			*20/20*	*1.1 – 19.6*	*9.5*	*9.6*
Krasnoyarsk Krai	*Khatanga*		*32/32*	*2.3 – 19.4*	*8.3*	*8.3*
Sakha Republic (Yakutia)			*127/85*	*2.4 – 33.3*	*9.6*	*9.8*
	Lena Delta		100/66	2.4 – 33.3	8.6	8.2
	Kolyma		27/19	5.3 – 22.7	13.2	12.6
Total			**2,167/1,833**	**0 – 1,130**	**14.1**	**10.8**

Author contribution

LS lead the DOC data collection and synthesis, created the database and led the writing of the manuscript. LS and GG conducted the literature search for appropriate DOC datasets. LS, CC, AM, JB, MF, UH, KSL, BH, JL, KWA, BJ, KF and GG
5   contributed so far unpublished DOC data for this study. LS and CC performed statistical analyses. All co-authors contributed to the writing.

Competing interests

The authors declare that they have no conflict of interest.

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