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

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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 Using published data and unpublished datasets from the author team we report regional DOC differences linked to latitude, permafrost zones, ecoregions, geology, near-surface soil organic carbon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~~between lake DOC concentration and lake 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 lakes in regions with ice-rich syngenetic permafrost deposits (yedoma) ~~lakes~~ compared to non-yedoma lakes ~~. Compared to previous studies we found~~ and a weak significant relationship between~~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 (C) sink for thousands of years since freezing is one of the most effective mechanisms for long-term C~~carbon~~ fixation in soils (Schuur et al., 2008; Grosse et al., 2011). Permafrost landscapes store large amounts (~1,300~~-~~ to 1,600 Pg C) of soil organic C~~carbon~~ (Hugelius et al., 2014) and are a potential source for C~~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 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 °C +/- 0.12 °~~-~~C over the 2007-2016 period due to higher air temperatures, with some of the strongest warming trends (about 0.9 °~~-~~C per decade) measured in individual boreholes at the polar stations Marre Sale in northwest Siberia and Samoylov Island in northeast Siberia (Biskaborn et al., 2019). In addition, thermokarst and thermo-erosion processes act as a mechanism for the rapid release of permafrost C~~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 C~~carbon~~ 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), and their biochemical processes play an important role for C~~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 C~~carbon~~ fractions (Tranvik et al., 2009). It is mobile and can be chemically labile (Vonk et al., 2013a, b). 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 (OC) content of terrestrial soils is the main source for allochthonuous DOC. ~~Because DOC is mobile and can be chemically labile (Vonk et al., 2013a, b), large amounts of~~ DOC in lakes can be ~~are~~ trans~~ported~~ferred to and stored ~~into lakes, where they can be either stored in~~ in lake sediments due to flocculation (Tranvik et al., 2009). DOC can also be ~~or mineralized~~ degraded by photo oxidation or microbial activity, resulting in the mineralization of OC to~~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~~These processes are important components of the ~~global~~northern C~~carbon~~ cycle and ~~contributes to the~~affect greenhouse gas emissions from lakes~~effect (Finlay et al., 2006)~~. Vonk et al. (2015) suggested that ~~this form of~~the C~~carbon~~ flux from surface waters to the atmosphere and from land to ocean represents roughly one third to one-half of the net ~~carbon~~ C exchange from land to the atmosphere in the Arctic.

Numerous studies estimated ~~organic carbon~~OC 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 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).~~

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 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 (Sobek et al., 2007). Hence, a pan-Arctic focused analysis of the spatial variability of lake DOC in permafrost regions is still missing.

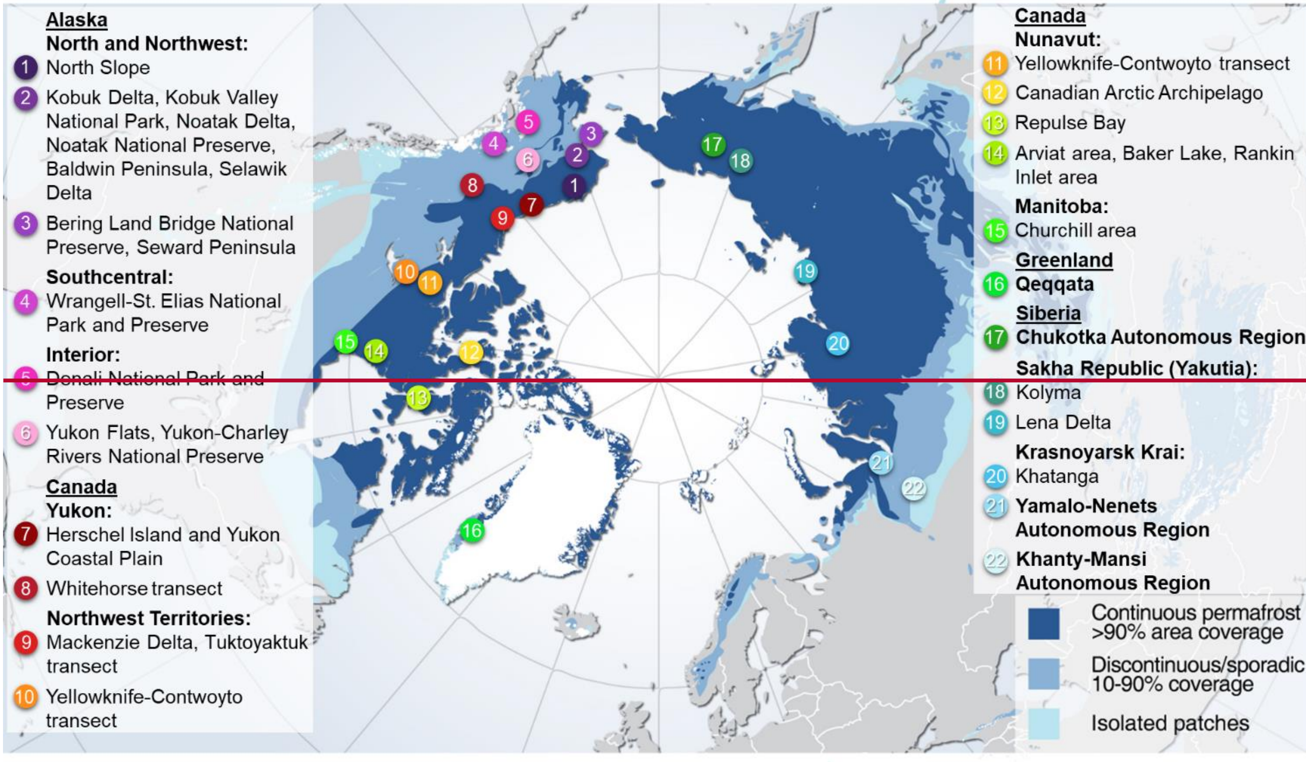
The objectives of this study are to synthesize existing datasets of lake DOC in northern permafrost regions, to provide first insights for linkages between DOC concentration and environmental parameters (permafrost zone, ecoregion, deposit types, ground ice content and soil organic carbon content), and 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, Fig. A1). 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. The study areas of our dataset are dominated by tundra climate and very cold subarctic climate. The Nunavut study area is also characterized by cool continental climate. The mean annual air temperature of our study areas ranges from -18 °C in the Canadian Arctic Archipelago (Michel, 2011) to -0.7 °C in Whitehorse, Yukon (Bonnaventure & Lewkowicz, 2011). All study lakes are located in landscapes influenced by permafrost (Fig. 1a). Lakes in this synthesis cover the full range of permafrost extents from continuous, discontinuous, isolated, and sporadic permafrost areas.

Study sites of the North and Northwest Alaska study area (Fig. 1a, 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. 1a, 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. 1a, 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. 1a, 5). The Interior Alaska study area is ~~affected by very cold subarctic to tundra climate and is~~ situated in the boreal zone and ~~. This area is~~ mainly underlain by fluvial (55 ~~-~~%) and yedoma (16 ~~-~~%) deposits.

The study sites in the Yukon and Northwest Territories study areas (Fig. 1a, 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.


Alaska
North and Northwest:
1 North Slope
2 Kobuk Delta, Kobuk Valley National Park, Noatak Delta, Noatak National Preserve, Baldwin Peninsula, Selawik Delta
3 Bering Land Bridge National Preserve, Seward Peninsula
Southcentral:
4 Wrangell-St. Elias National Park and Preserve
Interior:
5 Denali National Park and Preserve
6 Yukon Flats, Yukon-Charley Rivers National Preserve
Canada
Yukon:
7 Herschel Island and Yukon Coastal Plain
8 Whitehorse transect
Northwest Territories:
9 Mackenzie Delta, Tuktoyaktuk transect
10 Yellowknife-Contwoyto transect
Canada
Nunavut:
11 Yellowknife-Contwoyto transect
12 Canadian Arctic Archipelago
13 Repulse Bay
14 Arviat area, Baker Lake, Rankin Inlet area
Manitoba:
15 Churchill area
Greenland
16 Qeqqata
Siberia
17 Chukotka Autonomous Region
Sakha Republic (Yakutia):
18 Kolyma
19 Lena Delta
Krasnoyarsk Krai:
20 Khatanga
21 Yamalo-Nenets Autonomous Region
22 Khanty-Mansi Autonomous Region
Continuous permafrost >90% area coverage
Discontinuous/sporadic 10-90% coverage
Isolated patches

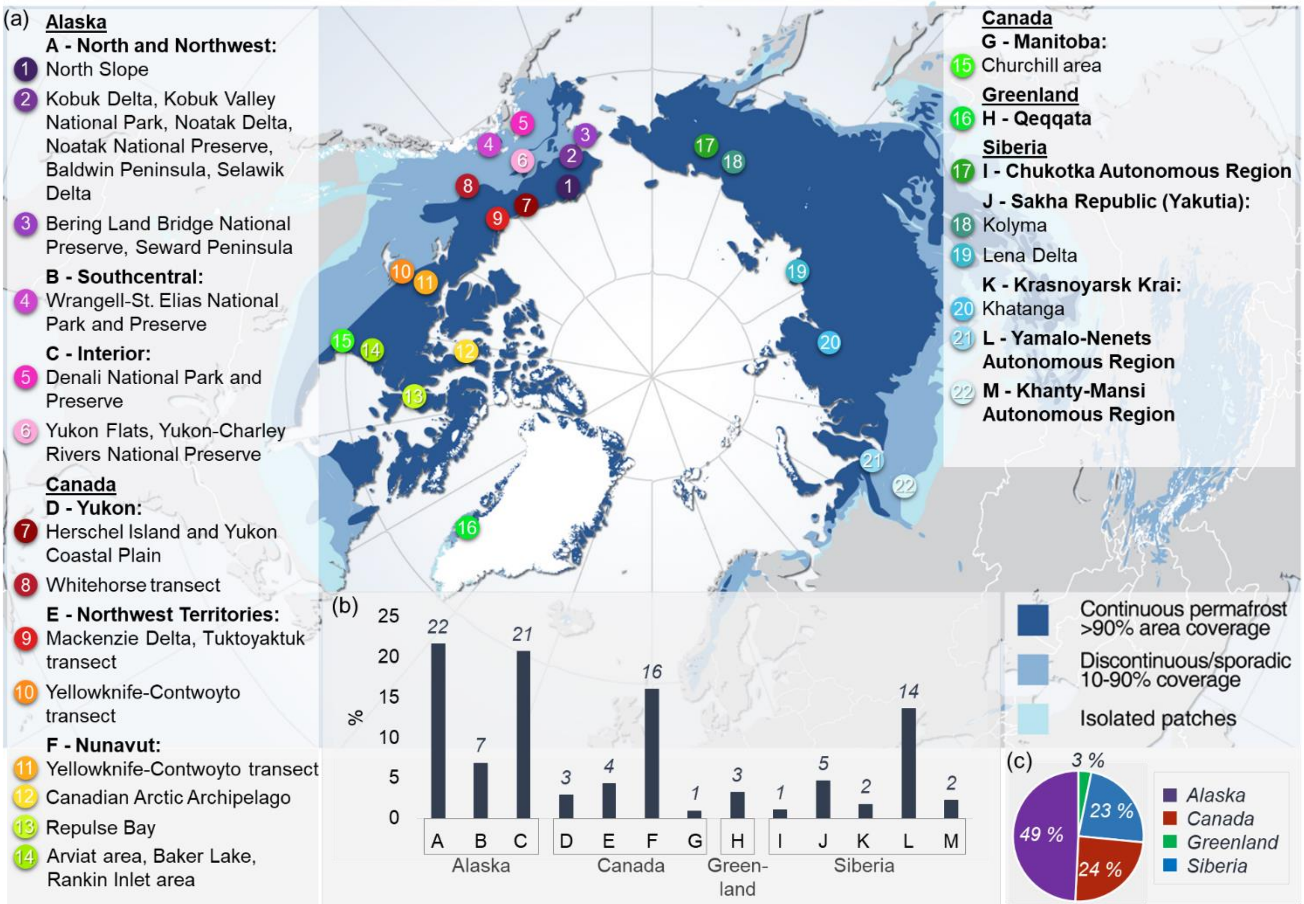


Figure 1: Overview of study regions (underlined bold font), study areas (bold font) and sites overlain of the map of permafrost zones (a), histogram of the amount of lakes in percentage by the study area in our dataset (b), and pie chart of lake distribution in the dataset by overarching regions (c) (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. 1a, 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 deposits. Studied lakes of the Manitoba study area (Fig. 1a, 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. 1a, 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.

The Siberian Yamalo-Nenets Autonomous Region (A.R.) study area (Fig. 1a, 21) covers the continuous, discontinuous and sporadic permafrost zones~~ and is affected by subarctic climate~~. 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. 1a, 22) are situated in the continuous and isolated permafrost zone. This area is situated in the boreal forest and dominated by glacio-fluvial deposits.

Table 1: ~~**Summary of DOC sample size and regional lake distribution**~~ **Overview of temporal sample distribution for each study area. Number in brackets are numbers of samples collected in each year**.

	Study area	Months of sample collection	Years of sample collection (number of samples)
Greenland	Qeqqata	April~~June~~ – August	2002 (10), 2003 (23), 2009 (5), 2013(20), 2014(23)
Siberia	Yamalo-Nenets Autonomous Region	June - August	1999 (8), 2000 (17), -2001 (1), 2010 (14), 2011 (43), 2013 (93), 2015 (24), 2016 (49)
	Khanty-Mansi Autonomous Region	July - August	1999 (21), 2000 (1), - 2001 (1), 2016 (18)
	Chukotka Autonomous Region	July	2016 (20)
	Krasnoyarsk Krai	July - August	2013 (32)
	Sakha Republic (Yakutia)	July - October	2002 (27), 2013 (3), 2014 (38), 2016 (59)
Canada	Yukon	July - August	1990 (22), 2012 (3), 2013 (6), 2014 (22), 2015 (1)~~-2016~~
	Northwest Territories	July, September	1990 (37), 1991 (20), 2004 (22)
	Nunavut	June - September	1979 (5), 1980 (17), 1983 (17), 1984 (2), -1985 (21), 1989 (22), 1990 (6), 1991 (4), 1992 (17), 1993 (22), 1994 (22), 1995 (20), 1996 (5), -1997 (7)~~, 1999, 2006-2010,~~ 2017 (19)
	Manitoba	July - August	2006-2010 (17)
Alaska	North and Northwest	June - September	2008 (15), 2009 (30), 2010 (2), 2011 (71), 2012 (98), 2013 (56), 2014 (115), 2015 (10), -2016 (102)
	Southcentral	May - September	2009 (25), 2010 (9), -2011 (96), 2015 (4), 2016 (4)

Interior	May - September	2003 (13), 2004 (14), 2005 (14), 2006 (30), 2007 (35), -2008 (92), 2010 (65), 2011 (63), -2012 (60), 2013 (36), 2014 (13), 2015 (20), -2016 (72)

~~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 deposits.~~ The Chukotka A.R. study area (Fig. 1a, 17) is situated in the continuous permafrost zone and ~~is characterized by subarctic to tundra climate. Studied lakes in this study area~~ covers the full range of tundra ecoregion, boreal forest and tundra-boreal transition region. Lakes in this study area~~, and~~ are surrounded by ice-rich syngenetic permafrost deposits (yedoma) and fluvial deposits. The Khatanga study site in the Krasnoyarsk Krai study area (Fig. 1a, 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 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 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~~April to early October (Table 1). If there was a lake sampled once in a month for more than one year, we calculated the average lake DOC concentration. Samples from the author team were taken from or near the water surface as well as the vast majority of the synthesized data. Although, some of the synthesized data do not provide the sampling depth we can assume that the majority of these arctic lakes and ponds are shallow and well mixed. 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, described in ~~(~~Appendix A~~)~~.

3.2 Sample database and geospatial analysis

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-DOCv1 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 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 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~~Brown et al., 1997). Finally, we used the Northern Circumpolar Soil Carbon Database (NCSCDv2) to add the soil organic carbon content (SOCC) 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).

3.3 Statistical Analysis

To conduct statistical tests, we used RStudio (version 1.0.153). We tested ~~N~~normality ~~was tested~~ by using the Shapiro–Wilk ~~normality~~ test. Because our~~the~~ data does not follow a normal distribution, we used the Spearman rank correlation coefficient (ρ) to measure ~~the~~ each relationship between ~~two variables~~DOC concentration and a further parameter (latitude, permafrost zone, ecoregion, ground ice content, deposit type, SOCC) for all lakes in our dataset. ~~and~~We used the Wilcoxon-Mann-Whitney test to determine the difference in means between two populations. To analyse the relationship of DOC and multiple parameters we performed a principal component analysis (PCA). Our dataset contains six samples from Qeqqata on Greenland (Osburn et al., 2017), collected in April with under-ice conditions. For the sake of comparability, these data have not been included in the statistical analysis.

4 Results

4.1 Temporal variability of DOC concentration data

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 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}.~~

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~~.~~ and ~~F~~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.

In our dataset, 16 lakes were sampled multiple times over the same seasonal period in the study site North Slope in North Alaska and six lakes were sampled multiple times over the same seasonal period in the study area Qeqqata, Greenland (Osburn et al., 2017). The six lakes located in Qeqqata were sampled in April, June and August in 2014, whereas lakes on North Slope were sampled in mid-June, end-June, in July and August in 2014. For five of the six lakes in Qeqqata, the highest DOC concentration of the respective sampling series was found for April samples. Then, the DOC concentration decreased in June and increased in August (Table 2). For these lakes, a 30 % to 45 % higher DOC concentration in April and up to 25 % higher DOC concentration in August was observed in comparison to the June sampling and therefore demonstrates a seasonal DOC variability.

Table 2: DOC concentration of six lakes from Qeqqata, Greenland, sampled three times in 2014 (Osburn et al., 2017) and 16 lakes from North Slope, Alaska, samples four times in 2014.

Region	Study area	Lake name	DOC concentration [mg L^{-1}]				
			April	Mid-June	End-June	July	August
Greenland	Qeqqata	SS906	8	5.2			5.8
		SS1381	39.2	24			31.3
		SS2	35.1	23.8			27.7
		SS8	52.5	28.7			38.3
		SS904	8.1	5.2			5.8
		SS1590	31.1	36.6			25
Alaska	North and	Hannahbear		5.5	6.5	2.7	1.7
	Northwest	Ini-001		0.4	2.5	0	0.2
		Ini-002		12.9	20.8	19.7	16.7
		Ini-003		0.5	0.3	0	0
		Ini-004		6.5	4.5	0.7	0.4
		Ini-005		4.7	4.7	3.4	3.1
		Ini-006		0	0.2	0	0
		LonelyWolf		1.6	2.1	0.1	1.3
		CrazyBear		0.9	2.2	1.6	0
		Duckfish		2.1	1.4	0.7	0.7
		FC-L9811		0	1.9	0	
		FC-L9819		3.6	1.2	0	
		FC-L9820		4.6	6.5	2.7	2.5
		FC-M9925		2.5	2.6	1.3	2.3
		FC-MC7916		5.3	3.5	0.8	0.6
		FC-R0066		0.8	1.9	8.7	0

~~Overall, the multi-temporal subset is very small and these results should be treated with care due to the low sample numbers.~~ In contrast to the Qeqqata samples we found decreasing DOC concentrations in 12 of 16 lakes on the North Slope comparing DOC concentrations of mid-June and August samples (Table 2). We also checked for seasonal variability in a larger dataset available from the study areas Southcentral and Interior Alaska where different sets of lakes were sampled during each month from May to September. This allowed an analysis of the median DOC concentration for each month for each of the two study areas. For Southcentral Alaska we found a pattern similar to that in Qeqqata with a 17 % higher DOC concentration in May and September compared to July (Table A2). Additionally, we compared samples of the whole dataset from the months June and August. For these months, in addition to the Qeqqata and North Slope samples, samples from the study areas Yamalo-Nenets A.R., North and Northwest Alaska, Southcentral and Interior Alaska were available. In three of the four study areas we also found higher DOC concentrations in August than in June, comparable to the Qeqqata lakes.

4.2 Variable DOC concentrations across the Arctic

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 (Fig. 2, Fig. 3, Table A~~2~~3). 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 3~~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 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 3~~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

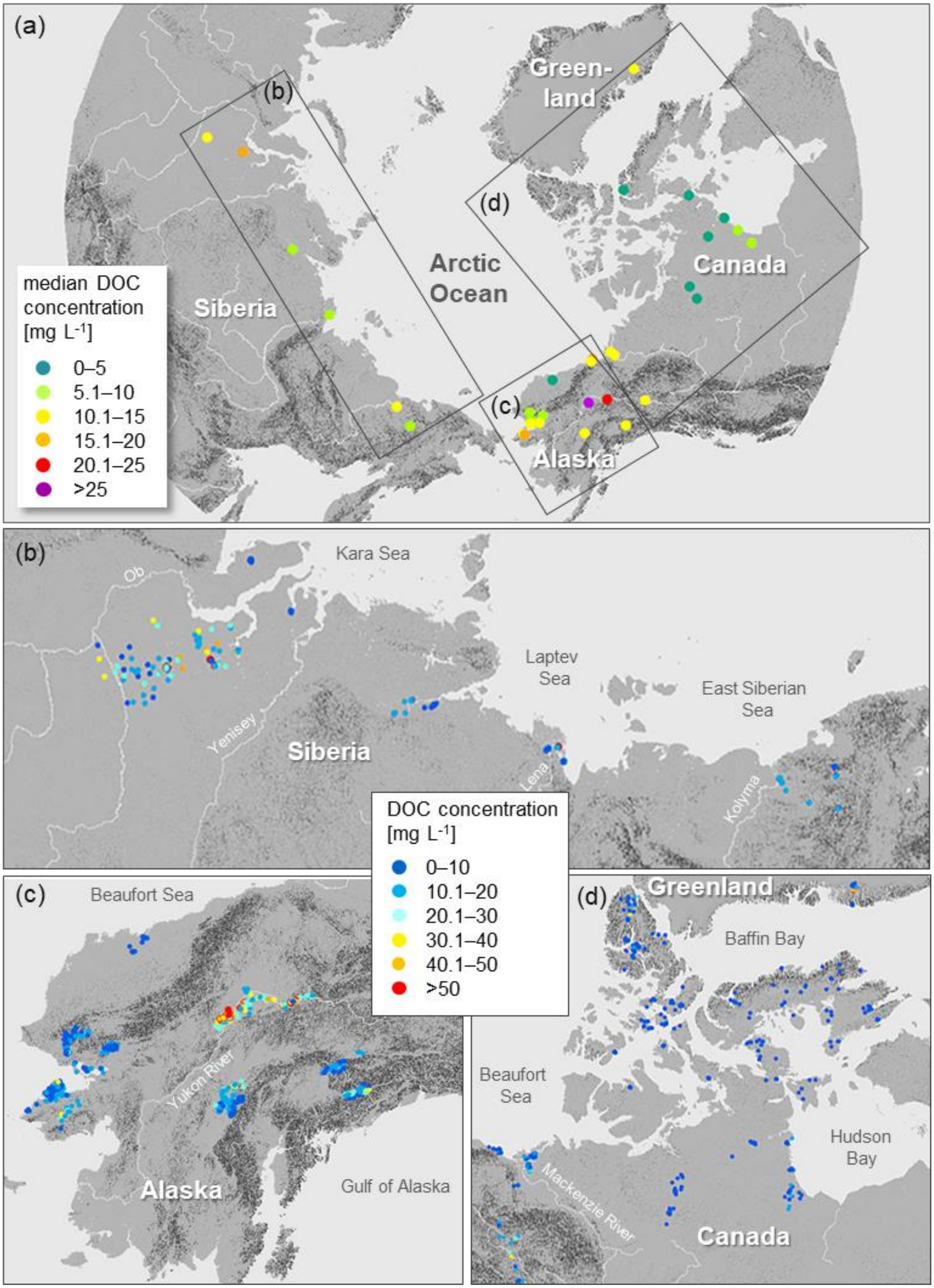


Figure 2: Map of lake DOC concentrations (mg L^{-1}) and regional variability. Median DOC concentration for each study site (a). DOC concentrations of individual lakes in the study regions Siberia (b), Alaska (c) and Canada and Greenland (d) (Background map: ESRI).

Figure 3~~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 had higher DOC concentrations than the dataset median. Lakes in Greenland showed a 50:50 ratio with DOC concentrations below and above the dataset median. A large number of lakes with DOC concentrations 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 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 4~~3~~; Fig. A2). 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 A3~~2~~).

Table 4: 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

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 4~~3~~; Fig. A2), 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 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

Median DOC concentration was~~ere~~ 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 4~~3~~; Fig. A2). DOC concentrations in lakes of the discontinuous zone were significantly higher (14 mg L^{-1}) than in 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). The DOC concentration~~s~~ 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}. 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 (ρ = -0.2; p < 0.05; Table 4; Fig. A2). 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 (ρ = 0.05; p < 0.05; Table 4; Fig. A2). 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.

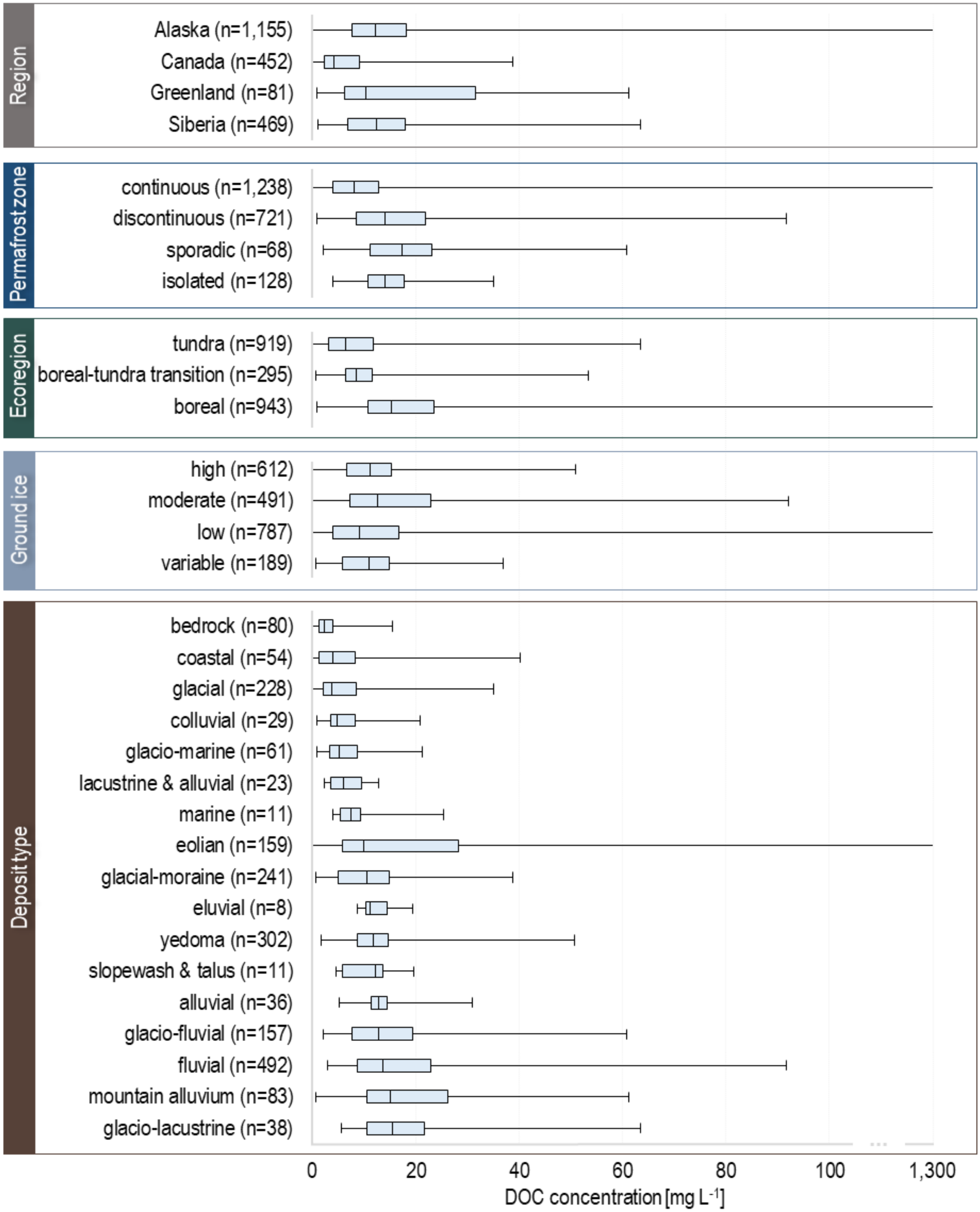


Figure 3: Dissolved Organic Carbon (DOC) concentration (mg L^{-1}) of lakes in different Arctic regions, permafrost zones, ecoregions, ground ice content, and deposit types. Note that the x-axis is interrupted between 100 mg L^{-1} and 1,300 mg L^{-1} to visually capture the wide range of the DOC concentrations.

~~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 (ρ = -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 (ρ = 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 SOCC~~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 (ρ = 0.1; *p* < 0.05; Table 4~~3~~; Fig. A2). The significance of the relationship was getting weaker for SOCC in the upper 300 ~~-~~cm (ρ = 0.09; *p* < 0.05; Table 4~~3~~, Fig. 4; Fig. A2).

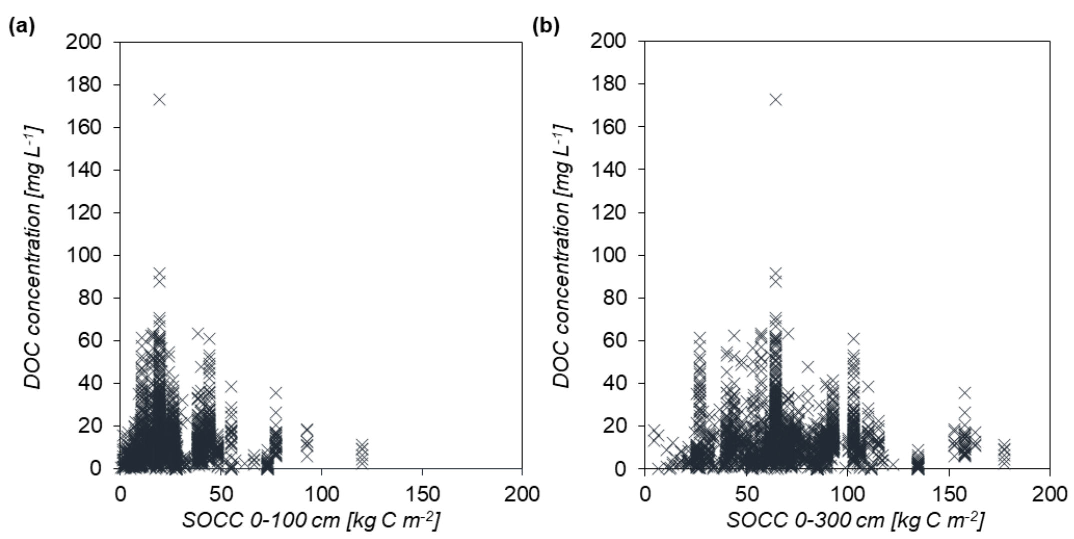


Figure 4: Scatterplots for lake DOC concentration and lake surrounding soil organic carbon content (SOCC) in a depth of 0 to 100 cm (a) and in a depth of 0 to 300 cm (b). To better visualize the relationship of both parameter we limited the y-axis to 200 mg L^{-1}. Three lakes with the DOC concentrations of 433 mg L^{-1}, 507 mg L^{-1} and 1,130 mg L^{-1} and SOCC of 19.7 kg C m^{-2} in a depth of 0-100 cm and 64.6 kg C m^{-2} in a depth of 0-300 cm are not included in this plot.

~~**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 (ρ = 0.31; ρ = 0.37; ρ = -0.3). In contrast to ~~other studies conducted at a smaller spatial scale (e.g. Harms et al., 2016; Larsen et al., 2017)~~Sobek et al. (2007), who assumed a strong relationship between lake DOC and soil OC, 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 particularly found that ~~particular~~ lakes in the boreal forest region 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~~ C 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 catchments on Herschel Island in Northwest Canada compared to a High Arctic catchments at Cape Bounty in~~,~~ Northeast Canada. This relationship may explain ~~In our database we found~~ high lake DOC concentrations we found in the Yukon Flats in Interior Alaska, a study area in the boreal forest ~~regions of Interior Alaska which are~~ and dominated by white and black spruce (Halm & Griffith, 2014). In contrast, higher permafrost extent in high~~er geographical~~ northern latitudes results in lower vegetation density and lakes are less connected and thereby hydrologically isolated, ~~and further in~~ leading to overall 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.~~

~~Changes in the structure of an ecosystem and biogeochemical fluxes due to lake DOC concentrations are affected by climate change~~With climate change affecting northern ecosystem structures, a reduced permafrost extent (Vasiliev et al., 2020), shifting vegetation composition (Myers-Smith et al., 2011), and enhanced hydrological connectivity (Chen et al., 2014; Nitze et al., 2017) likely will impact lake DOC concentrations and associated biogeochemical fluxes (Sobek et al., 2005). ~~This in turn, influences CO_2 emissions from these lakes and causes a positive feedback.~~For example, enhanced DOC concentrations in a lake provides an increased basis for the mineralization of DOC through photo oxidation and by microbial activity, which may result in higher CO_2 emissions from these lakes. ~~With~~In our first pan-Arctic assessment~~,~~ of DOC in lakes of the permafrost region we ~~can confirm~~found that DOC concentrations in lakes become significantly higher along an ecoregion gradient transitioning from tundra zone to the tundra-boreal transition zone to the boreal forest zone. In addition, DOC concentrations are overall higher ~~the~~in permafrost ~~region~~ zones that are less continuous. Both trends suggest that climate change, projected to result in an expansion of the boreal forest northwards into the tundra zone and a decrease in permafrost continuity will likely result in higher DOC concentrations in lakes of these regions. Moreover, permafrost loss and a shift of the boreal forest ecoregion might lead to more connected lakes and thus an increase of allochthonous DOC in lakes. This in turn, may result in higher CO_2 emissions from lakes to the atmosphere.~~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

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 area 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 by extensive low-lying wetlands. Though, we found a weak significant relationship between lake DOC concentration and lake surrounding deposit type, we found the lowest DOC concentrations in lakes surrounded by glacial and bedrock deposits (Fig. 3). In our dataset, these deposit types are mainly located in the former glaciated Canadian Arctic. ~~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) 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. So, we compared the DOC concentration in lakes of the yedoma region and the DOC concentration in lakes in non-yedoma regions, comprising 79 % of our dataset with different deposit types and including lakes with the four highest DOC concentrations in Interior Alaska characterized by fluvial deposits, eolian deposits and mountain alluvium deposits. We found significantly higher DOC concentrations in yedoma lakes compared to non-yedoma lakes. This might be attributed to the mobilization of old labile yedoma carbon by thermo-erosion along rapidly expanding lake shores and thermokarst processes (Strauss et al., 2017). We assume that yedoma lake generation is influencing yedoma lake DOC. The formation of yedoma lakes, due to deep thermokarst subsidence, results in deep and often closed basins (Morgenstern et al., 2011). As result of the missing lake connectivity, DOC is locked in the lake, originating partially from eroding organic-rich yedoma deposits (Strauss et al., 2017), melting yedoma ice wedges (Fritz et al., 2015) and from the active layer. Further the lower lake connectivity might prevent flushing of yedoma thermokarst lake water with river water and snowmelt water. Hence, we assume that yedoma thermokarst lakes are more likely to have elevated DOC concentrations than other more connected lakes as well as well-mixed larger and shallower lakes, where photodegradation plays an important role, associated with lower lake DOC concentration.

However, to determine the DOC source in yedoma lakes radiocarbon dating of each sample would be necessary. ~~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 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 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, the role of evaporation may also explain the high DOC concentrations of lakes in the Yukon Flats in Interior Alaska. Here, the lakes are less hydrologically connected and the region is very arid, allowing evaporation-driven concentration of DOC (Johnston et al., 2020).~~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~~another important indicator for lake DOC~~ regarding catchment properties~~, with lake DOC concentrations being lowest in areas of high elevation.

5.3 The complexity of lake DOC regulation

Analysis of our dataset with available pan-Arctic data have shown significant relationships between ecoregion and lake DOC concentration, between geographical latitude and DOC concentration, and between permafrost extent and DOC concentration, even if these relationships are generally weak. Other studies suggest additional parameters influencing lake DOC concentration. For example, Xenopoulos et al. (2003) analysed catchment characteristics of lakes and found that lake perimeter and the proportion of the watershed occupied by wetlands are strongest predictors for DOC in lakes of temperate forests. On a global scale, lake elevation and the proportion of wetlands in a watershed are strongest predictors for lake DOC. Tranvik et al. (2009) described that lake area, which is connected to lake volume and water retention time, might be negatively correlated in regional studies but that it is not an important DOC predictor in a global view. The fact that the majority of predictors for lake DOC differ in regions demonstrate the complexity of the regulation of DOC concentration in lakes. However, several of these parameters are not included in our study, which could be a cause for the often only weak relationships found in our analysis. As a result of limited data availability on detailed hydrological catchments of northern lakes, the hydrological connectivity (vertical and lateral) is also not included in our analysis. However, it is known for example that less allochthonous DOC is transported to a hydrologically isolated lake than to a connected lake (Bogard et al., 2019). In arid regions with rather isolated lakes, such as in the Yukon Flats in Interior Alaska, evapoconcentration of DOC plays an important role (Johnston et al., 2020). Water bodies with highest DOC concentrations in the Yukon Flats have a water depth less than 1 m. Studies in West-Siberia showed, that ponds receive the highest impact of allochthonous input due to the high ratio of lake drainage area vs. small water volumes. This results in short water residence time leading to highest concentrations of DOC (Shirokova et al., 2013; Manasypov et al., 2014, 2015). In addition to allochthonous DOC, autochthonous DOC, including phytoplankton productivity as well as heterotrophic bacterioplankton respiration processes (Chupakov et al., 2017), is influencing the DOC concentration, especially in lakes with low connectivity. For lakes in the Yukon River Basin, Bogard et al. (2019) described a minor importance of allochthonous DOC in lakes and highlighted the carbon fixation from atmospheric CO_2.

Beside our analysis of temporal variability of a subset of our dataset, the sampling month of each sample was not included in the statistical analysis of our pan-Arctic dataset, which may result in uncertainties due to variations in lake DOC concentration over the ice-free period. For Qeqqata, Greenland, higher DOC concentrations were found in samples collected in April (under ice) and August compared to June samples. In winter, nutrients as well as DOC do concentrate in lakes (Manasypov et al., 2015; Vonk et al., 2015; Grosbois et al., 2017), resulting in higher DOC concentrations in under-ice samples from April. The spring flood transports large amounts of allochthonous DOC to the lakes, concentrating them with DOC resulting in higher lake DOC concentrations in spring (Manasypov et al., 2015). During summer, in this region, characterised by low precipitation, evapoconcentration is a major cause for increasing DOC concentration (Anderson & Stedmon, 2007). Considering a seasonality of DOC concentration in our dataset, we found two different patterns in two different study sites. This highlights the complexity of regulators and mechanisms of the DOC concentration in a lake over a season.

The influence of biological, hydrological, climatic and topographical parameters on the DOC concentration of a lake clearly is very complex. Whereas our pan-Arctic dataset provides first insights of the relationship between some environmental parameter and lake DOC concentration, regional studies are necessary to understand these complex mechanisms and to determine DOC predictors, which may differ regionally.

5.4~~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~~ exceptional large number of lakes. This region hosts the most lake-rich landscapes on ~~E~~earth (Lehner ~~-~~& Döll, 2004) and their geologic and hydrologic origins are diverse (Pienitz et al., 2008; Vincent & Laybourne-Parry, 2008; Grosse et al., 2013) but often connected to paleogeographic and cryosphere processes that are differing substantially from the world's other lake regions (Smith et al., 2007; Brosius et al., 2021). Lakes in our synthesis dataset were sampled over the past 40 years (Fig. A1). Since then, environmental conditions in some study areas may have changed due to the accelerating climate change. For example, thermokarst lakes are very dynamic and some lakes that were sampled 30-40 years ago may be now be completely drained and thus no longer exist. Other environmental characteristics in catchments such as permafrost extent, vegetation cover, or runoff dynamics may have changed over time thereby also affecting lake DOC concentration. 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. To our best knowledge, there are no long-term lake DOC studies available for the Arctic that would help understanding decadal-scale DOC changes and trends and possible correlations with ongoing Arctic change. However, seasonal fluctuations were studied for a small subset of lakes in our dataset (Qeqqata, Greenland).

Further uncertainties result from still rather coarse-resolution 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 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~~ C fractions in lakes contributing to the greenhouse effect as part of the global ~~carbon~~ C cycle. This first pan-Arctic assessment provides linkages between DOC concentrations and the environment of 1,833 lakes in permafrost 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~~SOCC 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 lakes 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 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 for our dataset that ecoregion zonation is the most important driver for lake DOC concentration in the pan-Arctic region. Nevertheless, the regulation of lake DOC concentration is complex and some DOC predictors, such as hydrological connectivity, water retention time and topography, were not included in our analysis due to the lack of appropriately detailed pan-Arctic datasets for these parameters. However, ~~The new PerL-DOC database will be useful for quantification of carbon pools and fluxes from freshwater bodies across the Arctic. O~~our study of ~~the~~ pan-Arctic ~~assessment of~~ lake DOC concentration in permafrost regions provides a first broad overview of the connections between lake DOC and lake environment and forms~~provides~~ a basis for further detailed analysis. So, the new PerL-DOC database will be useful for quantification of C pools and fluxes from freshwater bodies across the Arctic.

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 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~~ C 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 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}.

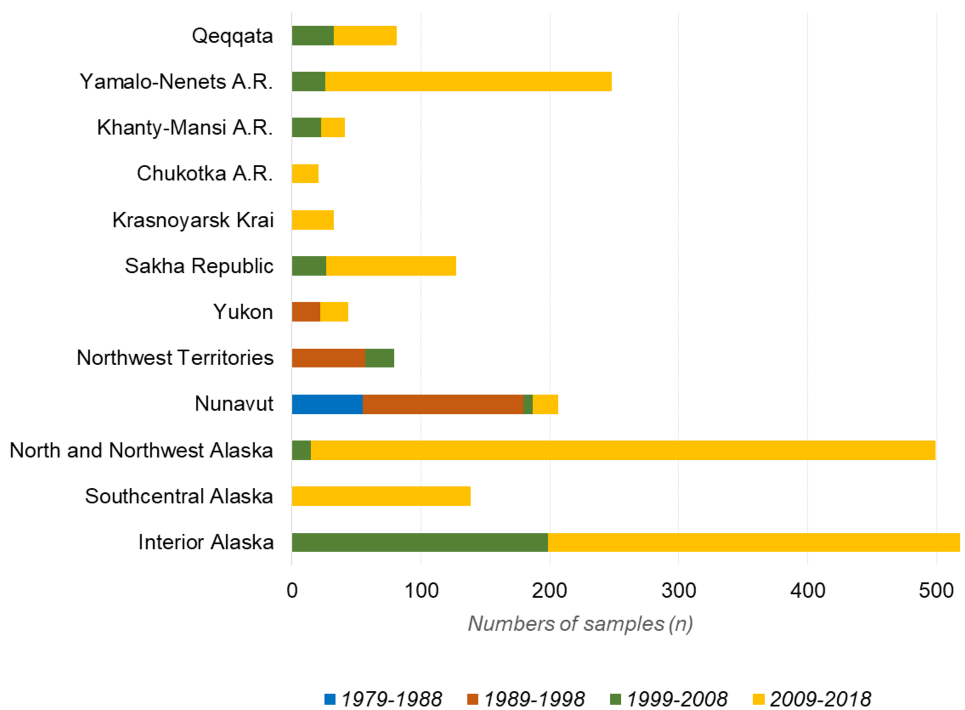


Figure A1: Histogram of numbers of samples in each study area per decade of sample collection. Since an exact allocation of the sampling year was not possible for 113 samples, these are missing in this figure for study areas Nunavut and Manitoba, Canada.

Table A1: Parameters for lake analyses.

General	Lake Name/ID	
	Sample date	
	Location	Latitude and Longitude.
	Study Area	Qeqqata, Yamalo-Nenets Autonomous Region~~Okrug~~, Khanty-Mansi Autonomous Region~~ Okrug~~, Chukotka Autonomous ~~Okrug~~Region, 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~~Region, Khanty-Mansi Autonomous ~~Okrug~~Region, Chukotka Autonomous ~~Okrug~~Region, 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, tundra-boreal transition, b~~B~~oreal f~~F~~orest ~~(Olson et al., 2004, link: 68635d7c77f1475f9b6c1d1dbe0a4c4c).~~
	Data Source	Reference or sample collector.
Hydrochemistry	DOC	In mg L^{-1}.
Geology	Deposit types~~s~~	Coastal, eolian, yedoma, glacial-moraine, glacio-lacustrine, glacio-fluvial, fluvial, mountain alluvium, glacio-marine, glacial, bedrock, colluvial, alluvial, lacustrine and alluvial, marine, eluvial, slopewash.
	Ground 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.

Table A2: Overview of median DOC concentration according to sampling months, where sampling month could be clearly identified.

	Study area	Median DOC concentration [mg L^{-1}]						
		April	May	June	July	August	September	October
Greenland	Qeqqata	33.1		10.2		25		
Siberia	Yamalo-Nenets Autonomous Region			18.1	29.6	13.9		
	Khanty-Mansi Autonomous Region				14.1	10.9		
	Chukotka Autonomous Region				9.6			
	Krasnoyarsk Krai				8.3	9.8		
	Sakha Republic (Yakutia)				8.1	10.2	7.8	15.3
Canada	Yukon				12.9			
	Northwest Territories				8.5		13	
	Nunavut				2.2	3.8	2.6	
Alaska	North and Northwest			4.5	9.1	8.2	8.1	
	Southcentral		15	13.6	12.5	16.3	15	
	Interior		12.7	18.4	12.6	20.3	21.3	

Table A~~2~~3: 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 Northwest		*499/397*	*0 – 53.3*	*9.6*	*8.6*
		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**

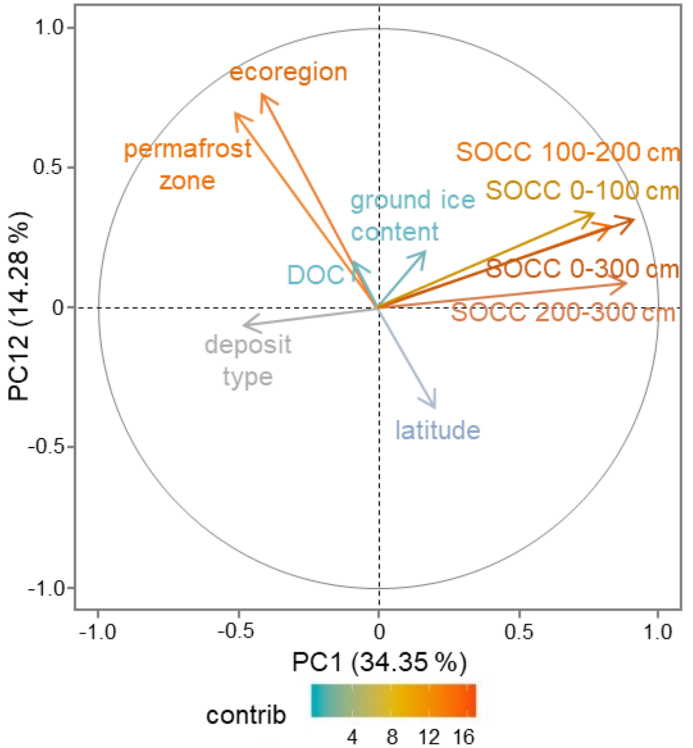


Figure A2: Principal component analysis showing a variables factor map with a color gradient showing the contribution to the plane construction. The first two principal components explained 34.35 % (PC1) and 14.28 % (PC2) of the variance in the analysed parameters (DOC, latitude, permafrost zone, ecoregion, ground ice content, deposit type, SOCC). The scores of PC1 had positive loadings with SOCC in all depths and negative loadings with deposit type, while PC2 scores had negative scores of latitude and positive scores of DOC, permafrost zone, ecoregion and ground ice content.

Data availability

The Permafrost Region Lake-DOC version 1 (PeRL-DOCv1) dataset was submitted to PANGAEA, is actually in the review process and will be available soon.

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 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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