Article

Patterns in the limnology of lakes and ponds across multiple local and regional environmental gradients in the eastern Canadian Arctic

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Abstract

This study examined water chemistry from 113 lakes and ponds across the eastern Canadian Arctic to address the lack of limnological data and understanding of relationships among limnological variables across key local and regional gradients. Environmental and geochemical variables were compared at both the local and regional scale with the use of multivariate analysis. A principal components analysis indicated that there was a primary gradient in temperature, nutrients, and conductivity between sampled regions. In addition, there were significant regional differences observed for nutrients total nitrogen (TN) and total phosphorus (TP), chlorophyll *a*, and dissolved major ions determined via canonical variates analysis. Across all regions TN:TP ratios were high, indicating phosphorus limitation, and mid-summer surface water temperature was strongly correlated to dissolved nitrogen concentrations. Local landscape characteristics were also examined, with multiple samples from lakes of varying elevations, surface area, and depth within the same area. Shallow pond systems (<2 m depth) were found to have significantly higher variability for major ions, especially in areas with influences from local geology. Likewise, the concentration of nutrients and ions in ponds were strongly correlated to concentrations of dissolved organic carbon, likely indicating the influence of watershed inputs and resuspended sediments on the limnology of ponds. Although there was higher regional variation in the limnology of pond systems than lakes, the general patterns within each region were similar.

Key words: Arctic, biogeochemistry, lakes, limnology, Nunavut, ponds, water chemistry

Introduction

Arctic ecosystems are defined by large seasonal transitions that control many thermodynamic relationships dependent on snow, ice cover, and solar radiation. The subsequent seasonal flow of energy is highly dependant on the underlying hydrology governed by the permafrost horizon. Because permafrost prevents water from infiltrating the groundwater system, the typical landscape of the eastern Canadian Arctic is dotted with numerous marshes, streams, lakes, and ponds that dominate its landscape. Arctic aquatic systems are therefore sensitive to long term changes in climate, and there is particular interest in identifying how changes in physical and chemical properties of freshwater bodies due to warmer climate promote changes in ecological interactions across trophic levels. Smol et al. (2005) suggested that shallow Arctic ponds could be the most sensitive aquatic system to climate warming depending on the amount, type, and timing of precipitation these systems receive. However, these types of predictions are difficult to assess in areas of the Arctic that have few, if any, direct observations.

The geochemistry of Arctic aquatic systems is likely strongly influenced by connections between terrestrial catchments, surface sediments, and bedrock composition (Hutchinson 1957, Wetzel 1983). Physical factors, such as

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topographic relief, depth, surface area, landscape position, and vegetation cover of catchment areas are important for hyporheic exchange, chemical weathering, and nutrient dynamics (Hamilton et al. 2001). The physical configuration and composition of drainage basins and catchment areas are also known to strongly control allochthonous inputs (Rasmussen et al. 1989). Thus, the spatial scale of watersheds also highly influences geochemical condition due to varying catchment to water volume ratios (Rasmussen et al. 1989). For example, dissolved organic carbon (DOC) concentrations in Arctic systems are known to be correlated to the amount of catchment vegetation present (Pienitz et al. 1997). In addition, Lim et al. (2001) found that shallow ponds on Bathurst Island had higher concentrations of DOC than deeper, and subsequently dilute, lakes with less vegetated catchments.

This study addresses the lack of limnological data and understanding of limnological relationships across key gradients in the eastern Canadian Arctic through an exploratory analysis of limnological patterns. We specifically sampled multiple lakes of varying size, depth, and catchment area characteristics within a relatively small spatial scale in an attempt to capture large local gradients that could have direct influence over their limnology. This sampling regime was then repeated over multiple areas to determine if the patterns in the limnology for local scales were representative of a larger spatial extent that crossed several ecoclimatic regions from the tree-line (northwest of Churchill, Manitoba) in the south, northward along the western coast of Hudson Bay, central Nunavut, and across several areas in the eastern Baffin region. Thus, this investigation addresses key questions about the limnology of the eastern Canadian Arctic over multiple scales: (1) Is there a regional difference in the limnology of lakes and ponds across a large spatial extent of the eastern Canadian Arctic? (2) How important are local landscape differences (e.g., surface area, depth) in terms of a system's limnology? (3) What are the key limnological relationships in lakes and ponds of the eastern Canadian Arctic?

Although several studies on the limnology of Arctic lakes and ponds are in the literature (Pienitz et al. 1997, Gregory-Eaves et al. 2000, Hamilton et al. 2001, Lim et al. 2001, 2005, Michelutti et al. 2002, Rühland et al. 2003, Westover et al. 2009), several large areas of the Canadian Arctic have little to no baseline data, and very few long-term monitoring sites exist for several vast regions. This is particularly the case for many of our sampling locations in the Kivalliq region of Nunavut. The lack of baseline limnological data makes it difficult to identify the environmental variables most important in structuring the biotic composition when there are potentially large local and regional differences in physical, landscape, and geochemical conditions.

Methods

Water samples were collected from 113 sampling locations (57 lakes and 56 ponds) within several areas of varying landscape and environmental characteristics. For our purposes, we used the classification of lakes and ponds based on their depth, with ponds classified by a mid-basin depth <2 m (Rouse et al. 1997, Lim et al. 2005). Sampling locations were conducted within similar geographic areas to maximize local gradients, and between areas that spanned from the tree-line area northwest of Churchill, Manitoba, extending northward across the Kivalliq region to the northeastern islands of the Baffin region (Fig. 1). Each location was characterized by variations in landscape characteristics, from the relatively flat (mean elevation of 12 m a.s.l.) western Hudson Bay region, to the relatively high relief areas of the Baffin region (mean elevation 100 m a.s.l.).

The soils of the eastern Canadian Arctic are poorly developed due to recent deglaciation and the presence of permafrost (Rühland et al. 2003). The majority of surficial materials in the areas we sampled are characterized by silty, sandy, and clay glacial deposits in either a till blanket (thick and continuous glacial deposits) or till veneer (typically discontinuous, thin, and often with widespread rock outcrops). The surficial material surrounding lakes in the southern coastal western Hudson Bay area varied between till blanket and coarse-grained glaciomarine deposits (Fulton 1995). The underlying geology also differs between our sampling locations, with the central Baker Lake area dominated by Archean metamorphic granite or diorite underlying 75% of the study lakes, and Archean sedimentary clastic or carbonate rock and volcanic igneous rock underlying 25% of the study lakes (Stockwell et al. 1976, Hanmer et al. 2004). Most of the lakes sampled in the Rankin Inlet area are underlain by Archean volcanic igneous rock, and Archean intrusive granitoid rock in the Arviat area. The majority of lakes in the area south of Arviat and just north of tree-line are characterized by till blanket surficial materials (Fulton 1995) with Archean metamorphic gneiss underlying more than half of the study lakes (Wheeler et al. 1997). The Baffin region is characterized by Proterozoic intrusive granitoid and Archean metamorphic gneiss bedrock (Wheeler et al. 1997), and the sediment composition varies between till blanket, fine-grained, and till veneer surficial materials (Fulton 1995).

Vegetation was primarily represented by numerous grass species (e.g., *Poa arcticus*, *Festuca rubra*, and *Elymus* spp.), matted compact cushions of prickly saxifraga (*Saxifraga tricuspidata*), and moss campion (*Silene acaulis*). Catchments consisted of moss cushions of several grasses and tundra plants intermixed with

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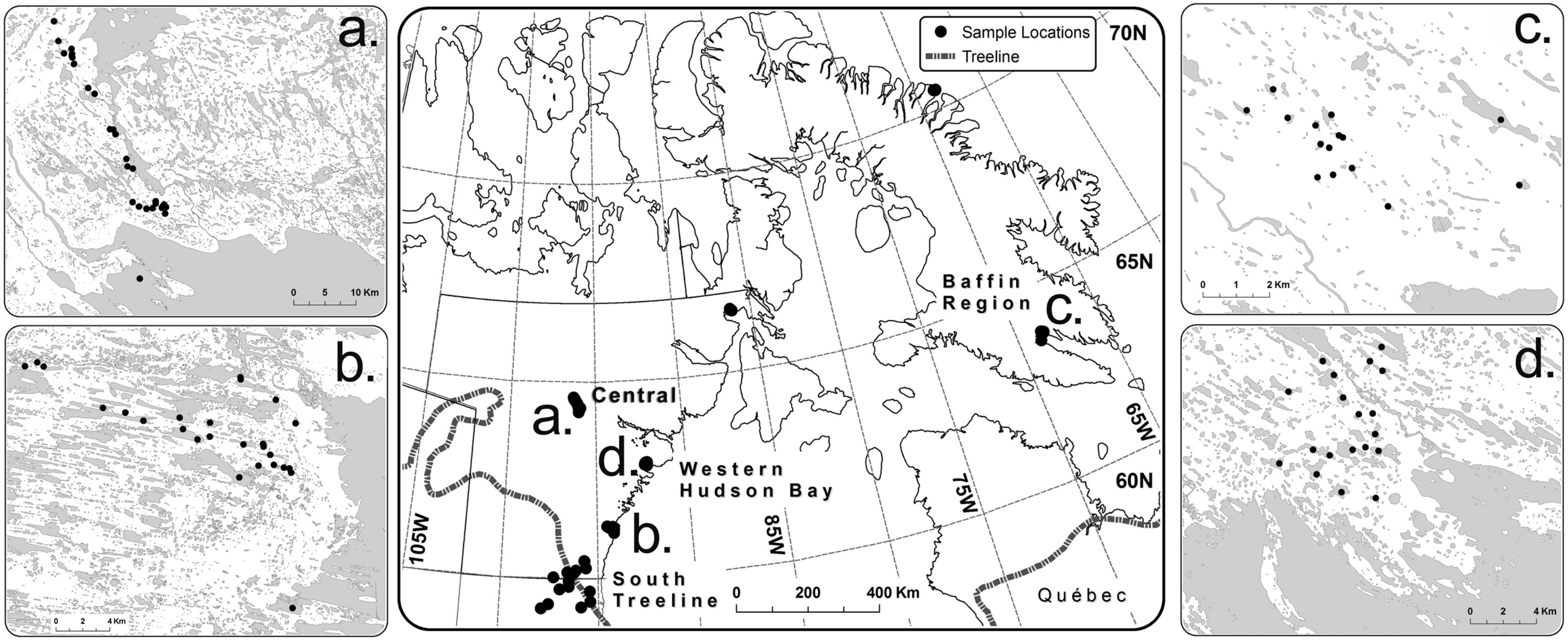

Fig. 1. Location of sampling areas identified by region: (a) central Kivalliq, (b) western Hudson Bay–Arviat area, (c) western Hudson Bay–Rankin Inlet area, (d) Baffin region–Iqaluit area. Not all sampling locations have an inset map.

clumps of dwarf fireweed (*Chamerion latifolium*). Large stands of *Salix* spp. shrubs, approximately 1.0–1.5 m in height, were also frequently present in catchment areas in southern regions. Dominant shrubs were found throughout the vicinity of the southern portion of the Hudson Bay region and tree-line region, which contrasted with other areas sampled in the central Kivalliq region and eastern Baffin region where the number and height of shrubs observed were less prominent.

Field sampling

Sampling was conducted during mid-summer (mid-Jul to mid-Aug) in each of the years 2006–2010. Physicochemical variables were measured using a YSI-600QS multi-parameter probe, including water temperature, specific conductance at 25 °C (COND), pH, and oxidation reduction potential (ORP). Depth was measured with a depth sounder, and the GPS location of each mid-basin was recorded. Epilimnetic water samples were collected at 0.5 m below the water surface in precleaned, HCl acid-washed, polyethylene bottles and immediately treated in the field following the protocols outlined in the Analytic Methods Manual of Environment Canada (Environment Canada 1994a).

Water samples for each lake and pond sample were analysed using standard operating procedures (SOP 02-2002) for major ions and nutrients (Environment Canada 1994a), as well as total and dissolved trace metals in water (Environment Canada 1994b) by in-bottle digestion and inductively coupled plasma (ICP) mass spectrometry and ICP-optical emission spectrometry by the National Laboratory for Environmental Testing at the Canadian Centre for Inland Waters, Burlington, Canada. In total, 55 variables were measured including: chlorophyll *a* (Chl-*a*) uncorrected for phaeophytin, dissolved inorganic carbon (DIC), particulate organic carbon (POC), particulate organic nitrogen (PON), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), chloride (Cl), total nitrogen unfiltered (TN), nitrate (NO_3), nitrite (NO_2), ammonia (NH_3), sulphate (SO_4), total phosphorus unfiltered (TP), silver (Ag), aluminum (Al), arsenic (As), boron (B), barium (Ba), beryllium (Be), bismuth (Bi), cerium (Ce), cadmium (Cd), cesium (Cs), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), gallium (Ga), lanthanum (La), lithium (Li), manganese (Mn), molybdenum (Mo), niobium (Nb), nickel (Ni), lead (Pb), platinum (Pt), rubidium (Rb), antimony (Sb), selenium (Se), tin (Sn), strontium (Sr), thallium (Tl), tungsten (W), uranium (U), vanadium (V), and zinc (Zn).

The water samples were filtered through a 47 mm GFC filter (pore size 1.2 µm) for Chl-*a* and 25 mm GFC filter for POC, and PON, wrapped in aluminum foil, frozen, and stored until analysis. There are limitations to sampling single point measurements within a season, and caution should be taken when comparing variables that may have a seasonal and interannual variability (e.g., Chl-*a*).

Data screening

Variables that had concentrations below the detection limit in a majority of sites sampled (e.g., NO_3, NO_2, SRP, Ag, Be, Bi, Cs, Li, Nb, Pt, Se, Sn, and Tl) were deleted from the dataset, and half of the detection limit was substituted for use in numerical analysis for those variables that had concentrations below the detection limit in less than half the samples. Trace metals with extremely low concentrations (<0.05 µg L^{-1}), and which were highly collinear (determined by unconstrained ordinations) with other environmental variables, were also removed from analysis (Cd, Cs, Co, Cr, Ga, La, Mo, Sb, Tl, and V).

Trace metal variables, as well as POC and PON, were missing from 12 lakes and 4 ponds sampled in 2006 due to loss of samples during shipping. Thus, analysis was conducted on a subset of the data to account for these missing samples, as well as on the full dataset. Environmental variables were transformed and checked for normality with a Kolmogorov-Smirnov test. Surface area, depth, COND, Cl, Ca, SO_4, DOC, Mg, K, Na, Al, As, B, Ba, Cu, Fe, Mn, Ni, Pb, Rb, Sr, U, and Zn were log(x+1) transformed, while elevation, ORP, NH_3, Chl-*a*, SiO_2, DIC, TN, and TP were square-root transformed. Temperature and pH data were found to have normal distributions; therefore, no transformation of these data was conducted.

Numerical analyses

A principal components analysis (PCA) was performed to determine the prominent environmental and limnological gradients in the dataset, as well as to observe whether there was a separation of site locations based on specific variables. PCAs were performed using CANOCO v4.53 (ter Braak and Šmilauer 1998), with variables centered and standardized. Geographical and nonlimnological explanatory variables for limnological variation such as latitude, elevation, and mid-summer surface water temperature (MSSWT) were passively run, as well as Chl-*a* (biological response variable). Na was also run passively due to the high correlation between Na and Cl ($r = 0.99$). The first and second principal components (PC1 and PC2) accounted for 44.7 and 22.0% of the variance, respectively. The third and fourth principal components accounted for 10 and 7.2% of the dataset variance and are not discussed further. Because several samples lacked the full water chemistry data (trace metals), a second PCA was conducted on both the reduced

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dataset excluding lakes without trace metal analysis, as well as on the full dataset excluding trace metals.

Because regionality was observed by the clustering of sampling locations visible from the PCA, a canonical variates analysis (CVA) was used to identify linear combinations of statistically significant limnological variables that best discriminated among the observed clusters. Variables that were collinear with other variables (highly correlated) were sequentially removed in a backward selection procedure until variance inflation factors were <10 (ter Braak and Šmilauer 1998). Physical, geographical, and landscape descriptors (e.g., depth, latitude, surface area, and elevation) were excluded from the CVA analysis. Because there was little difference between a CVA conducted on the full dataset of variables (excluding lakes without trace metal analysis available) and the reduced dataset of variables (excluding trace metal variables), we chose to present the results that included the metal analysis. The statistical differences in limnological variables between clusters (henceforth referred to as limnological regions) identified by the CVA were further identified using one-way analysis of variance (ANOVA) with a Tukey *post-hoc* test.

The PCA also identified several additional potential relationships between environmental and limnological variables, including a separation of sites based on depth, specifically those classified as pond systems (<2 m mid-basin depth) rather than lakes. Thus, further exploratory analysis was subsequently conducted for (1) all sampling locations, (2) only lake samples, and (3) only pond samples. Relationships between environmental and limnological variables (Table 1) were examined through a Pearson correlation matrix with sequential Bonferroni correction (Rice 1989), and individual environmental variables were evaluated with a series of reduced major axis regressions performed using PAST 1.61 (Hamilton et al. 2001). Ratios of TN:TP were calculated to indicate potential nutrient limitation, and Na:K ratios were calculated to relate to the influence of catchment vegetation (McNeely et al. 1979).

Results

Regionality

The PCA of limnological data identified a strong separation of the 113 lake and pond samples along a primary gradient of conductivity, nutrients, and temperature. Lakes and ponds were found to be clustered into 4 regional groups, which we classified as tree-line, central Kivalliq, western Hudson Bay, and Baffin regions (Fig. 1). The Baffin region is oriented on the left of the PCA, and the western Hudson Bay region along the far right (Fig. 2). This primarily corresponds to the first PC axis, which represents positive associations between TP, TN, and variables associated with ionic concentration (e.g., Ca, Cl, Mg, K, SO_4, Na, and DIC) with PC1. Conversely, lakes reflective of higher elevation, ORP, and depth were negatively associated with ionic concentration and are representative of lakes found in the Baffin region (Fig. 2). Gradients found along PC2 primarily consisted of a positive relationship with DOC, TP, and Chl-*a*, and negative relationships with SiO_2, DIC, Ca, and pH. The differentiation of higher temperatures and productivity from those with higher inorganic inputs was primarily observed in lakes and ponds in the southern tree-line region, which were oriented in the upper-left quadrant of the PCA (Fig. 2). This also reflected the larger depth and surface area and lower concentration of ions for lakes in this inland region. Lakes and ponds sampled in the central Kivalliq region were primarily found in the center of the PCA, with the exception of larger lakes (e.g., Baker Lake) that were found grouped with the larger lakes of the southern and Baffin regions (Fig. 2).

CVA using backward elimination indicated that temperature, Rb, and TN were the strongest variables distinguishing between regions (Table 2). The first CVA axis accounted for 38.2% of the variance and primarily represented the difference between lakes and ponds in the warmer Hudson Bay region that had higher concentrations of Rb and TN oriented to the right of the ordination (Fig. 3). The second CVA axis accounted for 33.8% of the variance and was represented by lakes and ponds in the tree-line region that had higher concentrations of DOC and Mg found in the upper quadrant of the ordination, compared to lakes in the Baffin region that had significantly higher pH and COND found in the lower-left quadrant (Table 2; Fig. 3). Although we sampled 2 distinct areas of western Hudson Bay, the vicinity of Arviat (Fig, 1b) and the vicinity of Rankin Inlet (Fig, 1d), there was little difference found in the limnology of these 2 areas in either the PCA or CVA analysis (Fig. 2 and 3). Thus, samples from Arviat and Rankin Inlet were grouped into the western Hudson Bay region for discussion.

Local characteristics

The PCA biplot of sample locations revealed a difference in the limnology for shallow ponds versus lake systems where shallow systems were found to have a higher variance for several variables (e.g., COND, DIC, TP, and TN), which separated some ponds from lakes along the first and second axis (Fig 2). The difference in the limnology between regions for several variables (e.g., POC, PON, and Chl-*a*) was only observable after separating shallow pond systems (<2 m deep) from deeper

Table 1. Selected environmental and limnological data for the 113 sampling locations ordered by latitude. Full dataset is available in supplementary materials.

	Physical							Major ions			Nutrients and Organics			
Site	Lat **DD°**	Long **DD°**	Area **ha**	Elev **m**	Depth **m**	MSSWT **°C**	pH	COND µS cm^{-1}	Ca mg L^{-1}	DIC mg L^{-1}	DOC mg L^{-1}	Chl-*a* µg L^{-1}	TP µg L^{-1}	TN µg L^{-1}
CH16	59.23	−97.89	28.3	246	1.0	20.8	6.3	20	1.9	3.2	16.9	3.2	16.4	703
CH03	59.27	−95.86	2214.5	105	4.5	12.7	8.6	17	1.3	1.3	5.7	1.9	5.7	308
CH19	59.34	−97.52	12.6	263	1.3	20.1	6.6	13	1.3	2.4	10.5	2.7	13.6	503
CH01	59.41	−95.41	690.0	65	4.5	12.2	7.7	1	1.3	2.5	7.0	1.6	5.3	282
CH02	59.67	−95.43	1195.1	70	2.6	15.1	8.2	3	1.3	2.4	4.3	2.6	5.9	289
CH15	59.73	−96.97	1256.6	221	2.3	18.9	6.5	9	0.7	2.0	11.3	1.4	5.9	271
CH14	59.73	−96.96	1.8	224	1.9	18.3	6.4	8	0.7	2.8	8.8	1.2	14.3	953
CH09	59.79	−96.49	515.2	192	2.9	12.9	7.2	13	0.9	2.6	6.3	1.0	7.1	298
CH18	59.92	−96.51	314.2	181	8.8	17.7	6.9	12	1.1	1.3	21.2	0.8	2.9	177
CH17	59.93	−96.51	12.8	181	1.5	19.6	6.3	17	1.6	2.1	13.7	2.7	8.5	481
CH08	60.03	−97.28	282.1	260	2.7	12.6	7.5	8	1.3	1.3	6.4	2.1	5.0	316
CH07	60.15	−96.57	159.2	194	1.4	12.2	7.5	9	1.1	1.1	5.4	1.3	4.4	265
CH13	60.16	−96.21	283.5	132	1.7	20.2	6.8	16	1.3	2.4	7.0	1.1	7.9	321
CH06	60.21	−96.14	1064.2	140	2.3	12.2	7.2	10	0.9	1.5	3.6	1.9	7.1	276
CH04	60.27	−95.62	1798.3	100	5.0	12.2	7.5	13	1.2	2.1	5.3	1.9	5.4	291
CH05	60.44	−95.69	226.2	100	4.0	12.0	7.3	12	0.9	1.2	2.7	1.3	5.2	221
CH11	60.45	−95.70	0.1	96	0.8	20.8	7.1	25	1.7	2.3	17.8	0.7	9.4	604
AV01	61.15	−94.12	251.8	4	1.5	17.9	7.6	1006	12.1	5.8	4.5	1.2	14.3	486
AV03	61.24	−94.19	591.7	14	3.0	16.2	8.4	83	3.5	2.2	4.3	0.9	4.6	354
AV26	61.24	−94.11	6.9	23	1.5	20.4	7.1	70	2.3	2.9	2.6	0.9	7.2	217
AV23	61.25	−94.12	35.0	20	0.7	18.7	8.0	65	5.3	4.4	9.2	3.7	16.1	811
AV25	61.25	−94.12	28.9	19	1.0	20.1	8.2	182	7.1	5.1	9.1	2.1	12.5	631
AV02	61.25	−94.16	57.0	11	0.5	14.1	8.2	90	4.8	3.1	8.4	3.0	15.0	827
AV15	61.25	−94.14	88.1	15	1.0	22.0	7.0	73	3.2	3.0	6.4	1.1	12.2	516
AV04	61.26	−94.14	20.5	24	1.1	15.2	7.3	43	11.5	5.7	4.7	1.1	13.4	617
AV13	61.26	−94.15	57.4	9	1.0	19.3	6.4	95	8.8	6.5	10.9	2.3	11.2	960
AV05	61.26	−94.18	45.4	21	2.0	16.7	8.3	74	6.3	4.7	8.1	1.3	7.8	527
AV14	61.26	−94.15	51.2	11	0.8	22.0	7.6	120	9.8	5.4	11.7	2.8	12.2	921
AV06	61.27	−94.24	179.0	13	2.0	17.3	7.8	144	4.1	5.3	4.7	1.1	5.7	379
AV24	61.27	−94.23	54.1	20	1.5	19.7	7.7	138	13.3	8.2	10.8	1.6	12.2	817
AV12	61.28	−94.11	11.8	11	0.8	19.0	6.8	146	9.5	5.9	11.3	1.1	12.8	811
AV11	61.28	−94.23	42.0	20	0.5	15.5	8.4	121	9.9	6.5	5.2	0.4	7.3	439
AV09	61.28	−94.32	350.1	21	6.0	18.3	7.1	69	3.4	2.1	4.0	1.3	6.5	381
AV07	61.28	−94.27	448.3	11	1.7	15.7	8.5	240	6.5	5.3	4.2	0.5	5.7	327
AV16	61.29	−94.35	56.4	32	1.5	21.7	7.4	75	6.3	5.8	7.1	1.0	7.8	521
AV08	61.29	−94.38	18.4	23	1.5	18.3	7.1	87	8.4	4.5	5.2	1.1	9.8	469
AV19	61.29	−94.13	2361.0	10	5.0	19.4	7.8	116	4.9	3.9	4.0	1.0	8.6	376
AV18	61.31	−94.18	575.6	6	2.5	18.8	7.9	205	5.8	4.3	4.8	1.9	9.7	314

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Table 1. Continued

	Physical							Major ions			Nutrients and Organics			
Site	Lat **DD°**	Long **DD°**	Area **ha**	Elev **m**	Depth **m**	MSSWT **°C**	pH	COND μS cm^{-1}	Ca mg L^{-1}	DIC mg L^{-1}	DOC mg L^{-1}	Chl-*a* μg L^{-1}	TP μg L^{-1}	TN μg L^{-1}
AV17	61.31	−94.18	4620.1	14	5.8	19.4	7.5	99	3.9	3.1	5.8	1.6	7.5	338
AV21	61.32	−94.46	390.8	33	4.0	17.9	8.6	16	1.6	2.0	2.6	1.3	6.4	312
AV22	61.32	−94.49	72.9	19	1.9	18.7	7.9	77	3.9	5.1	6.4	2.9	15.0	717
AV20	61.32	−94.47	105.9	18	1.8	16.8	8.0	73	4.2	3.0	7.2	1.5	11.1	527
RA18	62.84	−92.18	1.4	42	0.4	13.0	8.1	179	26.3	16.0	9.9	1.7	7.3	694
RA17	62.84	−92.22	60.6	14	5.5	12.3	8.1	255	27.5	15.9	5.4	0.9	8.1	458
RA19	62.85	−92.25	61.8	16	9.3	12.4	7.2	180	13.5	9.1	3.5	1.6	9.0	438
RA20	62.86	−92.29	37.4	14	2.5	15.5	7.3	92	14.3	12.5	4.0	1.8	10.2	392
RA15	62.86	−92.23	32.6	18	2.2	15.1	7.8	73	6.8	4.8	17.4	1.6	10.2	374
RA08	62.87	−92.17	86.7	31	7.4	13.9	7.3	101	7.4	4.4	3.4	1.6	5.5	294
RA13	62.87	−92.21	90.8	16	8.7	13.6	7.0	74	6.6	3.7	3.3	1.1	5.3	309
RA14	62.87	−92.19	1.6	8	0.2	11.9	8.2	256	17.1	8.4	9.7	2.1	9.4	705
RA16	62.87	−92.25	30.9	18	2.9	15.1	7.6	85	7.9	4.9	4.8	1.6	7.7	362
RA10	62.87	−92.18	31.2	12	1.0	15.7	7.8	135	10.8	7.0	6.6	3.3	14.6	583
RA03	62.89	−92.18	1.1	28	5.0	12.4	8.2	66	6.2	5.6	3.4	2.9	9.2	356
RA09	62.89	−92.20	3.2	11	0.2	17.8	8.3	479	19.1	9.1	6.5	1.5	7.2	407
RA05	62.9	−92.21	29.0	23	3.5	13.3	7.4	85	9.4	6.2	4.5	1.1	5.8	380
RA06	62.9	−92.28	64.9	54	4.2	12.6	7.6	40	3.8	2.8	3.5	0.9	4.4	293
RA04	62.91	−92.22	96.0	23	3.0	13.1	7.6	78	8.4	5.1	10.7	1.6	8.4	403
RA11	62.91	−92.16	24.6	34	3.2	14.2	7.2	111	9.3	5.1	4.6	0.8	5.1	544
RA07	62.92	−92.18	32.6	32	2.0	13.6	7.1	159	10.6	5.2	3.8	0.9	7.0	323
RA02	62.92	−92.23	29.8	13	4.0	15.6	7.1	74	9.6	6.2	3.7	1.2	13.1	507
RA12	62.92	−92.16	262.8	32	6.0	15.1	7.1	45	4.4	2.7	2.7	0.6	4.0	227
IQ10	63.59	−68.75	0.8	40	4.0	17.1	8.6	49	3.3	2.6	3.7	0.6	4.7	187
IQ04	63.76	−68.45	8.8	158	9.0	10.2	7.9	43	9.6	5.2	4.5	0.1	2.9	175
IQ11	63.77	−68.53	2.2	133	5.0	11.5	8.0	24	3.5	3.0	1.3	0.7	1.3	116
IQ05	63.78	−68.44	106.3	196	17.2	8.2	8.2	35	6.7	4.3	10.9	0.4	2.9	145
IQ06	63.78	−68.54	4.7	134	5.8	10.5	8.3	39	9.6	6.7	2.3	0.7	2.0	148
IQ01	63.78	−68.55	1.8	175	4.0	10.3	8.0	19	4.4	3.6	2.1	0.9	1.9	149
IQ13	63.78	−68.56	1.6	125	3.0	8.5	8.1	50	10.3	7.6	2.4	0.7	2.3	249
IQ18	63.79	−68.54	0.1	159	0.5	12.4	8.6	58	12.3	8.4	3.2	0.1	3.0	202
IQ03	63.79	−68.53	1.9	155	3.0	11.4	8.4	27	5.2	3.7	1.5	0.4	2.8	121
IQ02	63.79	−68.55	2.6	159	1.5	14.5	7.0	27	3.9	3.6	2.1	0.7	1.7	109
IQ17	63.8	−68.55	3.4	172	1.5	8.6	8.3	22	4.5	3.5	1.6	0.6	2.0	161
IQ20	63.8	−68.53	9.8	175	2.5	12.9	8.4	24	4.5	3.3	1.0	0.3	3.2	89
IQ12	63.8	−68.56	3.7	171	1.0	10.1	8.6	40	8.6	6.1	2.4	0.8	2.3	236
IQ15	63.81	−68.58	6.9	136	1.2	9.8	8.6	64	14.9	9.2	1.7	1.0	3.0	150
IQ14	63.81	−68.56	6.1	161	4.0	10.5	8.6	47	9.3	5.8	1.3	0.6	1.2	111

Table 1. Continued

	Physical							Major ions			Nutrients and Organics			
Site	Lat **DD°**	Long **DD°**	Area **ha**	Elev **m**	Depth **m**	MSSWT **°C**	pH	COND μS cm^{-1}	Ca mg L^{-1}	DIC mg L^{-1}	DOC mg L^{-1}	Chl-*a* μg L^{-1}	TP μg L^{-1}	TN μg L^{-1}
BL01	64.24	−95.99	188700	0	13.5	10.5	7.2	20	2.4	2.8	2.9	1.0	5.7	189
BL35	64.33	−95.90	5.0	53	1.6	13.1	8.4	32	5.1	5.3	3.5	0.5	5.3	260
BL02	64.34	−95.97	49.7	61	12.0	10.6	7.7	32	4.0	7.0	2.6	0.4	4.1	186
BL03	64.34	−95.94	15.6	70	2.5	11.0	8.4	48	5.0	4.4	3.2	0.9	4.9	235
BL36	64.34	−95.91	11.5	71	8.1	11.8	8.2	39	6.6	5.8	3.1	0.5	4.7	245
BL32	64.34	−95.90	1.9	75	0.9	10.1	8.4	20	2.9	3.7	4.0	1.4	5.8	269
BL04	64.34	−95.99	0.8	81	0.5	10.2	8.8	22	2.9	4.0	3.4	0.6	8.7	240
BL33	64.34	−95.91	3.2	71	0.9	7.8	8.2	18	3.0	4.0	2.9	1.3	7.4	261
BL34	64.35	−95.91	0.9	68	0.8	11.5	8.1	23	3.6	4.1	3.4	0.7	6.9	294
BL37	64.35	−95.93	7.4	77	2.8	13.8	8.4	53	8.2	6.7	3.1	1.1	5.3	288
BL06	64.35	−96.01	12.5	73	2.7	12.0	8.2	49	8.8	6.6	2.5	0.3	4.4	218
BL38	64.35	−95.93	6.9	74	2.9	14.4	8.7	56	9.0	8.1	3.8	2.3	7.2	356
BL08	64.4	−96.01	5.8	67	0.8	11.3	8.3	36	6.9	6.2	3.8	0.8	5.6	270
BL09	64.4	−96.03	2.6	67	0.9	10.4	8.4	25	4.9	4.5	3.4	1.0	4.9	233
BL11	64.41	−96.03	2.0	55	1.5	13.9	8.4	36	6.0	5.3	3.2	0.9	4.4	254
BL13	64.45	−96.07	14.8	50	1.0	11.8	8.4	39	5.2	5.0	2.6	1.2	6.1	230
BL15	64.46	−96.08	5.0	59	1.2	11.4	8.1	23	4.7	4.5	2.8	0.3	5.0	203
BL14	64.46	−96.09	20.1	56	1.2	10.0	8.2	22	3.7	3.7	3.8	0.6	4.4	224
BL16	64.51	−96.14	300.1	77	13.0	8.2	8.0	23	3.8	3.7	3.9	0.6	4.5	235
BL17	64.52	−96.16	1.9	81	1.1	14.6	8.3	77	6.8	4.3	5.4	0.5	5.6	396
BL23	64.55	−96.21	11.8	98	1.1	12.8	8.0	53	4.0	2.6	2.4	1.0	5.8	209
BL26	64.56	−96.22	13.2	101	1.0	7.5	8.0	37	4.5	3.9	3.0	0.6	4.0	232
BL25	64.56	−96.22	3.1	106	1.0	14.6	8.0	41	4.1	3.4	2.3	1.0	4.1	269
BL24	64.57	−96.22	11.1	97	1.0	11.3	8.3	66	6.1	3.5	2.2	0.5	4.5	205
BL28	64.57	−96.25	61.3	113	1.1	11.3	8.1	17	2.5	2.8	2.6	0.9	3.0	180
BL27	64.57	−96.22	3.2	103	1.2	7.2	8.2	37	4.0	3.5	4.7	0.9	5.1	290
BL29	64.58	−96.27	1.1	134	5.0	8.5	8.8	11	1.7	3.0	2.8	1.1	10.6	257
BL31	64.61	−96.28	51.4	150	4.0	10.7	8.0	19	2.5	2.3	2.2	0.5	3.0	141
RB01	66.53	−86.22	5.8	34	0.5	12.8	8.5	142	24.4	19.4	5.4	0.4	6.4	442
RB07	66.55	−86.26	7.9	58	7.2	10.3	8.5	83	18.2	13.4	2.8	0.6	9.1	317
RB02	66.55	−86.28	1.7	17	1.0	11.2	8.4	66	11.6	8.5	2.0	0.1	7.3	273
RB04	66.55	−86.31	6.8	150	1.1	13.7	8.9	56	9.7	7.9	4.2	0.4	4.7	355
RB14	66.56	−86.28	0.8	200	0.5	11.6	8.2	102	17.5	6.0	4.2	0.6	4.9	313
RB17	66.58	−86.32	2.2	76	0.5	12.0	8.5	95	17.1	13.8	4.1	0.1	7.0	345
CR01	70.46	−68.51	71.5	20	4.5	8.6	8.1	14	0.5	0.9	0.8	0.1	2.7	75
CR02	70.47	−68.47	5.0	18	2.0	10.5	7.6	6	0.2	0.6	0.6	0.3	2.9	76
CR04	70.48	−68.63	86.5	9	12.3	5.6	8.0	17	0.4	0.7	1.0	0.7	4.0	89

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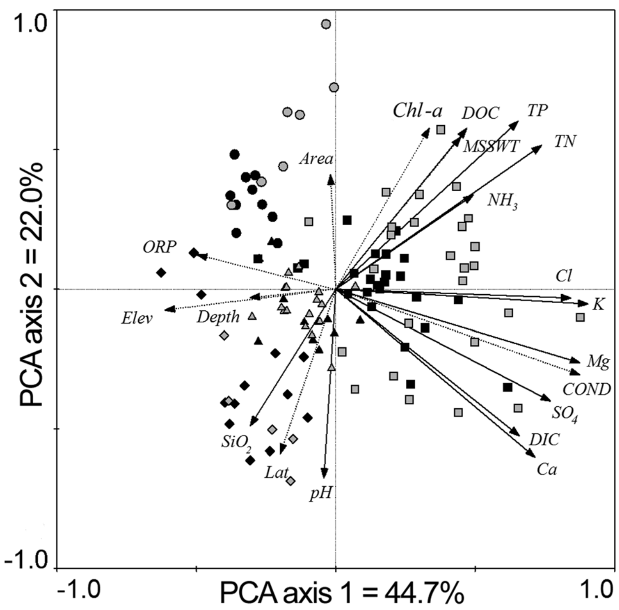

Fig. 2. Principal components analysis of significant environmental indicators (excluding metals) for the 113 sampling locations. Limnological variables run actively are indicated by solid lines, while physical and geographical variables run passively are indicated by dotted lines. Region classification: ● tree-line, ■ western Hudson Bay, ▲ central Kivalliq, and ◆ Baffin. Ponds are indicated by gray fill.

lake systems (Fig. 4). Although this difference between lakes and ponds was found to be significant, the median maximum depth of lakes was only 4.0 m (range 0.2–17.2 m) because most sampling locations were of moderate size with surface area ranging from 0.5 to 4620 ha (not including Baker Lake, 188 700 ha) for lakes (median 56 ha), and from 0.5 to 448 ha for ponds (median 9 ha).

When the limnology of each region was examined independently, results did not differ from the general relationships observed in the regional analysis. The variance in environmental variables in intra-regional PCAs was also large within each region, with the main differences being lake samples separating from ponds (Fig. 5). Ponds were generally associated with higher concentrations of major ions (Mg, Cl, and K) and metals (Cu, Al, Fe, Mn, Ni, and Sr). In addition, temperature and nutrient concentrations were the largest gradients in each region, with the exception of the Baffin region, which had a larger variance in ions and SiO_2 (Fig. 5). The large variance in the limnology of lakes and ponds within each area is likely due to the large variation in local landscape characteristics (depth, surface area, elevation).

The pH of lakes and ponds was similar, ranging from 6.3 to 8.9 (median 8.0). Larger, deeper lakes generally had a lower pH, and smaller shallow ponds were more alkaline.

Table 2. Canonical variates analysis (CVA) canonical coefficients, associated *t*-values, and interset correlations for significantly different limnological variables for the 97 sampling locations defined by region (sites without metals removed). Significant values to an associated axis are bolded (***P* < 0.05**). Abbreviations: Mid-summer surface water temperature (MSSWT), conductivity (COND), chloride (Cl), calcium (Ca), magnesium (Mg), silica (SiO_2), aluminum (Al), iron (Fe), manganese (Mn), rubidium (Rb), dissolved organic carbon (DOC), chlorophyll *a* (Chl-*a*), total unfiltered phosphorus (TP), total unfiltered nitrogen (TN).

	Canonical coefficient		*t*-values		Interset correlation	
	AX1	AX2	AX1	AX2	AX1	AX2
MSSWT	**0.4535**	0.0748	2.0567	0.3188	0.6111	0.3341
pH	0.0537	**−0.4541**	0.2960	−2.3533	−0.1741	−0.5465
COND	−0.4610	**−1.4297**	−1.2542	−3.6570	0.6430	−0.4895
Cl	0.1891	**−0.7002**	0.6055	−2.1074	0.6991	−0.2628
Ca	0.3892	−0.0810	1.2800	−0.2506	0.3815	−0.5631
Mg	0.2040	**0.9815**	0.6957	3.1475	0.6779	−0.2814
SiO_2	−0.0598	**−0.6205**	−0.3459	−3.3722	−0.3802	−0.3152
Al	−0.0998	0.1464	−0.5970	0.8232	0.1211	0.4170
Fe	−0.4329	0.4312	−1.8134	1.6982	0.1434	0.5366
Mn	−0.0949	0.0263	−0.4399	0.1148	0.0193	0.4080
Rb	**2.3616**	0.3738	8.1844	1.2181	0.9153	0.1241
DOC	−0.1679	**0.9664**	−0.7745	4.1905	0.3960	0.5742
Chl-*a*	−0.2382	0.1138	−1.3365	0.6004	0.3064	0.4731
TP	0.4734	−0.1986	1.5457	−0.6097	0.6607	0.3075
TN	0.1489	−0.4311	0.4086	−1.1125	0.6840	0.2868

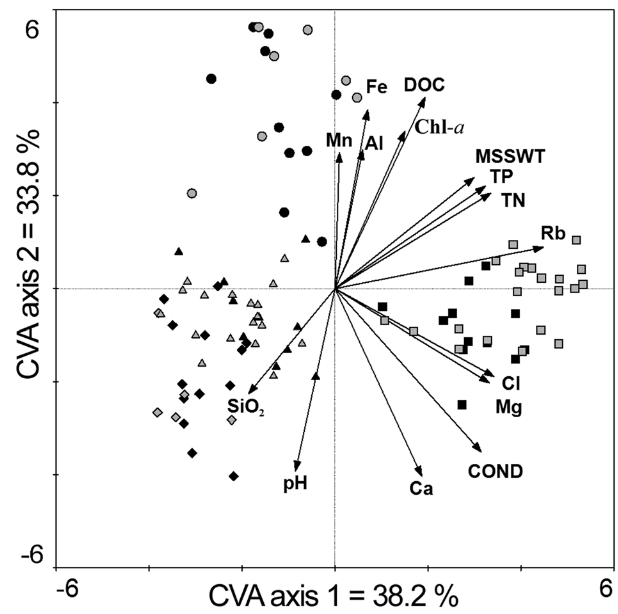

Fig. 3. Canonical variate analysis of significant environmental indicators (including metals) for the 97 sampling locations. Sites and variables are classified as in Fig 2.

Ponds with a higher alkalinity corresponded to higher concentrations of DIC and DOC, and a higher COND. The pH varied widely, but was generally highest in lakes and ponds in the central Nunavut region, and lowest in the tree-line area (Fig. 4). COND was also lowest in lakes closest to tree-line and highest in lakes in the western Hudson Bay region. As expected in systems with higher COND, concentrations of Mg, Sr, SO_4, Ca, B, and DIC were also high (Fig. 5). The most dilute samples were from deeper, larger lakes of high elevation (Fig 2). The relative anion concentrations were Cl > DIC > SO_4, with means of 12.4, 4.9, and 3.0 mg L^{-1} respectively. Concentrations of K ranged from 0.07 to 4.83 mg L^{-1} but varied greatly in lakes and ponds in the Hudson Bay region.

Key relationships

The largest variation between each region was for MSSWT and the concentration of TN and TP (Fig 4). MSSWT ranged from 5.5 to 22.0 °C, with a mean temperature of 13.9 °C. There was a 1.5 °C difference in MSSWT between lakes and ponds (mean 13.1 °C for all lakes, 14.7 °C for all ponds). The ratio of TN:TP was calculated to indicate whether lakes and ponds were phosphorus or nitrogen limited, with ratios by weight of TN:TP > 17 reflective of phosphorus limitation (Sakamoto 1966, Downing and McCauley 1992). Across all regions, TN:TP ranged from 22:1 to 108:1 (median 50:1) by weight, suggesting phosphorus limitation. Although there was little difference in the mean TN:TP ratio for lakes versus ponds, TN concentrations were found to be higher in warmer, shallow ponds in the tree-line and southern Hudson Bay regions (Fig. 4). Likewise, the regional variability in TN concentrations was higher in ponds than lake systems (Fig. 4).

Significant positive correlations were found between TN and temperature, conductivity (and associated ions; Cl, Ca, Mg, K), DOC, several metals (e.g., Rb, Ni, Fe), and a negative correlation was found with depth (Table 3). Similar to nitrogen, the concentration of TP was highest in the Hudson Bay region and lowest in the Baffin region (Fig. 4). In addition, while the concentration of TP was generally lower in lakes (median 5.3 µg L^{-1}) than ponds (median 7.2 µg L^{-1}), the regional variability of TP in pond systems was larger than in lake samples (Fig. 4).

In contrast to nutrients, Chl-*a* was similar for both lakes and ponds, ranging from 0.05 to 3.7 µg L^{-1} (median 1.0 µg.L^{-1}). The largest concentrations of Chl-*a* were found in lakes and ponds in the tree-line (median 1.6 µg L^{-1}) and western Hudson Bay regions (median 1.2 µg L^{-1}), with the highest variability observed in pond systems (Fig. 4). The corresponding relationship between Chl-*a* and nutrients was stronger than temperature, reflected by the significant correlations between Chl-*a* and TN, TP, and PON (Table 3). The importance of organically bound nutrients, and subsequent Chl-*a* concentrations, is reflected by the significant relationship between TP, DOC, and Chl-*a* (Fig. 6). In addition, larger concentrations of DOC were found in pond systems, with the highest variability in the southern Hudson Bay region (Fig. 4). In contrast, the concentrations of DIC were similar for both ponds and lakes but highly variable in the western Hudson Bay region (Fig. 4).

There were several noteworthy relationships between metals and environmental variables, with correlations between temperature and conductivity with B, Rb, and Sr (Table 3). There were also significant relationships between Fe and Chl-*a*, TN, and TP. Likewise, significant relationships were found between Rb and POC, PON, TN, and TP (Tables 2, 3). In addition, ponds with larger surface areas had positive relationships with temperature, DOC, and several elements (e.g., B, Rb, Sr) in contrast to deeper lake systems (Fig. 7).

A second PCA explored the variation of metal concentrations in a reduced subset of 97 lakes and ponds. The orientation of site locations, as well as the relationships between gradients, was similar to that of the full sample dataset (Fig. 7). Metals generally oriented to the right of the PCA, with Sr, Rb, B, and Ba associated to PC1, and Fe and Al reflective of PC2. The median concentration for metals was higher in ponds compared to samples from lakes. For example, the largest concentration of Fe was found in ponds sampled in the tree-line region

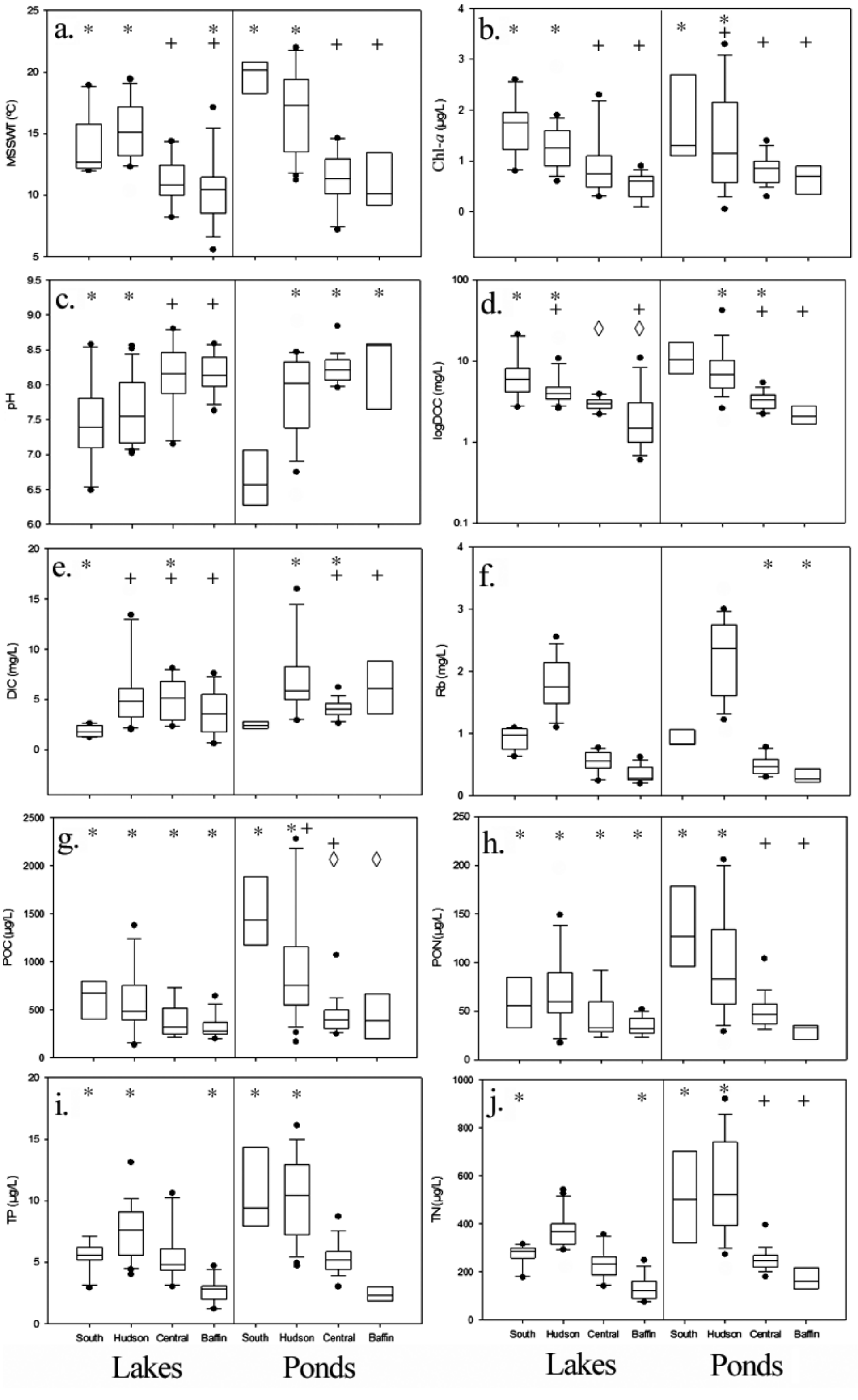

Fig. 4. Trends in selected environmental variables across identified regions. Sampling locations are organized by region, with lakes on the left and pond samples on the right. Significant regional differences in variables, identified by ANOVA, are indicated by the difference in symbols (*, +, ◊) between boxplots for (a) mid-summer surface water temperature (MSSWT), (b) chlorophyll *a* (Chl-*a*), (c) pH, (d) dissolved organic carbon (DOC), (e) dissolved inorganic carbon (DIC), (f) rubidium (Rb), (g) particulate organic carbon (POC), (h) particulate organic nitrogen (PON), (i) total phosphorus (TP), and (j) total nitrogen (TN).

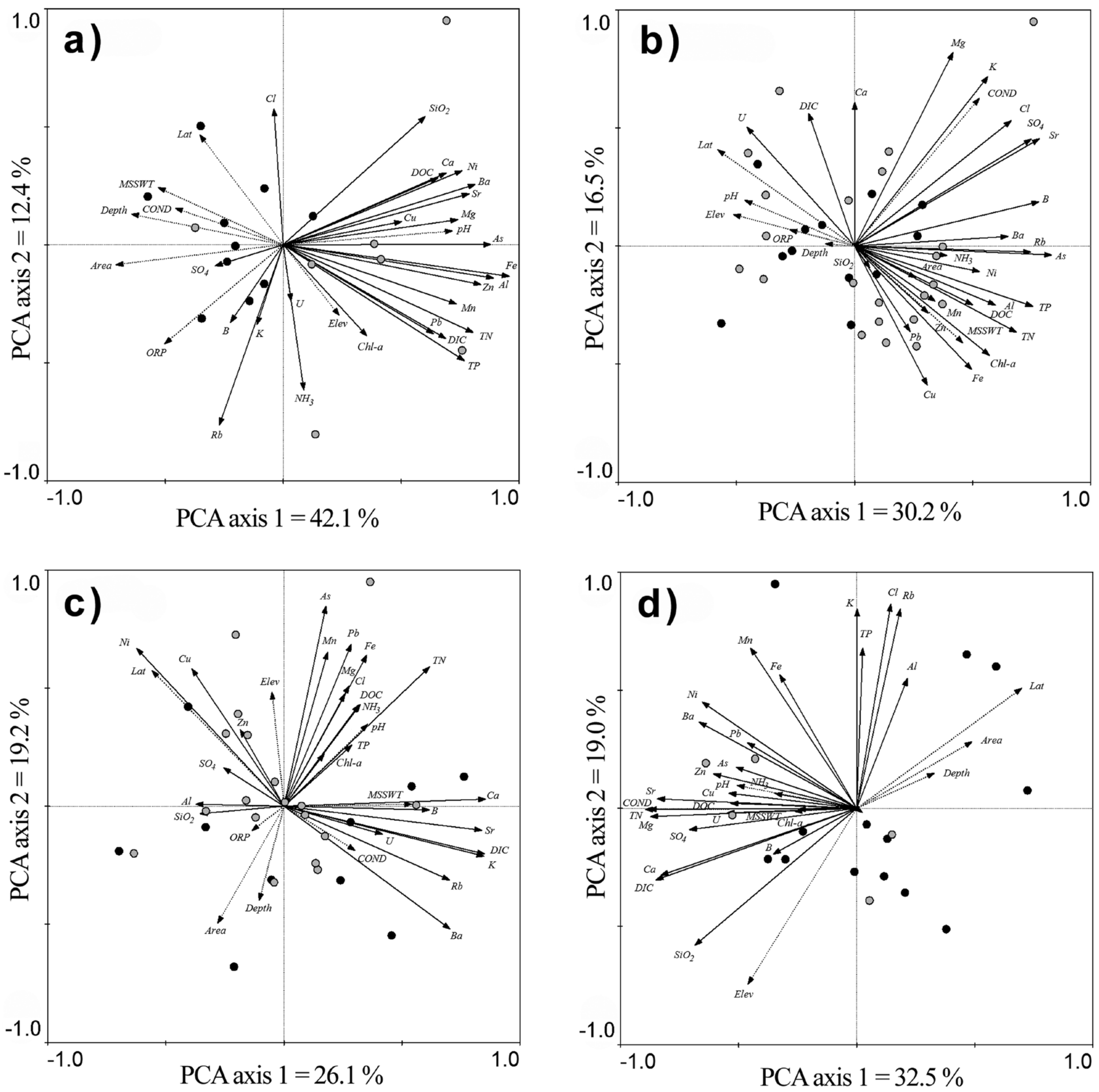

Fig. 5. Interregional principal components analysis of significant environmental indicators (including metals) for lakes and ponds (gray-fill) of the (a) tree-line region, (b) western Hudson Bay, (c) central Kivalliq, (d) and the Baffin region.

(median 354 µg L^{-1}) compared to western Hudson Bay (median 160 µg L^{-1}), the central Nunavut region (median 112 µg L^{-1}), and Baffin regions (median 52 µg L^{-1}).

Discussion

Regionality

While the limnology of vast areas of the Canadian Arctic is still unknown, our analysis indicates common patterns that may span multiple physiographic regions. Our sampling regime attempted to target gradients in the local physical and environmental characteristics as well as examine potential differences between pond systems and lakes. This allowed both inter- and intra-regional comparisons of the limnology of lakes and ponds independently. Pond systems generally had higher and more variable concentrations of nutrients, ions, and DOC than lake systems (Fig. 4); however, the overall relationships between nutrients, productivity, and DOC were similar for both lakes and ponds for most variables (Fig. 6). Large gradients were found in several major ions (B, Cl, K, and Mg), metals (Rb and Sr), and nutrients for both lakes and ponds in our dataset (Fig. 2). To a lesser extent, a gradient in pH, Chl-*a*, and metals (Al, Fe, and Mn) was also found along PC2 (Fig 2). The CVA analysis, however, indicated significant differences in temperature, Chl-*a*, nutrients, conductivity, and metals between regions (Fig 3).

Table 3. Pearson correlation matrix (*100) with sequential Bonferroni-adjusted probabilities of selected limnological variables. Bolded values indicate $\boldsymbol{P < 0.01}$, *italicized* values indicate $P < 0.05$. Abbreviations: Elevation (Elev), mid-summer surface water temperature (MSSWT), conductivity (COND), oxygen reduction potential (ORP), chloride (Cl), calcium (Ca), magnesium (Mg), potassium (K), silica (SiO_2), aluminum (Al), boron (B), iron (Fe), rubidium (Rb), strontium (Sr), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), chlorophyll *a* (Chl-*a*), particulate organic nitrogen (PON), particulate organic carbon (POC), total unfiltered phosphorus (TP), total unfiltered nitrogen (TN).

	SA	Elev	Depth	MSSWT	pH	COND	ORP	Cl	Ca	Mg	K	SiO_2	Al	B	Fe	Rb	Sr	DOC	DIC	Chl-*a*	PON	POC	TP
Elev	−36																						
Depth	*46*	−4																					
MSSWT	25	−31	−25																				
pH	−35	9	−13	**−52**																			
COND	−11	**−59**	−21	30	11																		
ORP	24	39	9	−23	−15	**−55**																	
Cl	13	**−73**	−16	*41*	−2	**85**	**−48**																
Ca	−36	−29	−22	−2	30	**80**	*−44*	**50**															
Mg	−4	**−51**	−28	31	11	**86**	−38	**82**	**71**														
K	7	**−64**	−18	33	−1	**84**	**−49**	**84**	**64**	**81**													
SiO_2	−38	*40*	−3	−27	20	−16	11	*−40*	16	−15	−48												
Al	20	−18	17	26	*−47*	−14	1	2	−31	−4	4	−14											
B	20	**−72**	−18	**51**	−4	**78**	*−42*	**82**	**49**	**77**	**81**	−22	9										
Fe	7	1	*−44*	**48**	−29	−11	3	5	−30	−4	0	−20	*42*	5									
Rb	*41*	**−67**	−22	**67**	−24	**60**	−25	**70**	27	**64**	**78**	*−45*	22	**79**	31								
Sr	−2	−55	−22	*40*	5	**85**	*−43*	**78**	**72**	**78**	**80**	−14	−11	**79**	−2	**56**							
DOC	23	−15	−20	**59**	−35	21	−18	29	4	26	31	−21	27	30	**55**	**54**	26						
DIC	*−39*	−21	−24	−2	29	**67**	−37	36	**92**	**61**	**57**	14	−26	*39*	−21	24	**63**	9					
Chl-*a*	30	−23	−13	*47*	−35	6	−3	21	−10	8	28	−34	*40*	22	**56**	*44*	16	**50**	−9				
PON	17	−22	−29	**55**	−26	7	−13	17	−18	9	10	−17	*45*	35	**59**	**54**	17	**49**	−13	**51**			
POC	19	−23	−31	**61**	−28	8	−13	19	−18	12	12	−19	*47*	*40*	**64**	**59**	20	**52**	−11	**53**	**98**		
TP	13	*−46*	−31	**61**	−35	25	−28	*44*	12	38	**51**	−41	**49**	**54**	**55**	**73**	*42*	**59**	18	**64**	**62**	**66**	
TN	5	*−39*	*−39*	**65**	−35	*44*	−30	**48**	29	*45*	**53**	−28	35	**56**	**56**	**76**	**49**	**69**	31	**61**	**63**	**65**	**85**

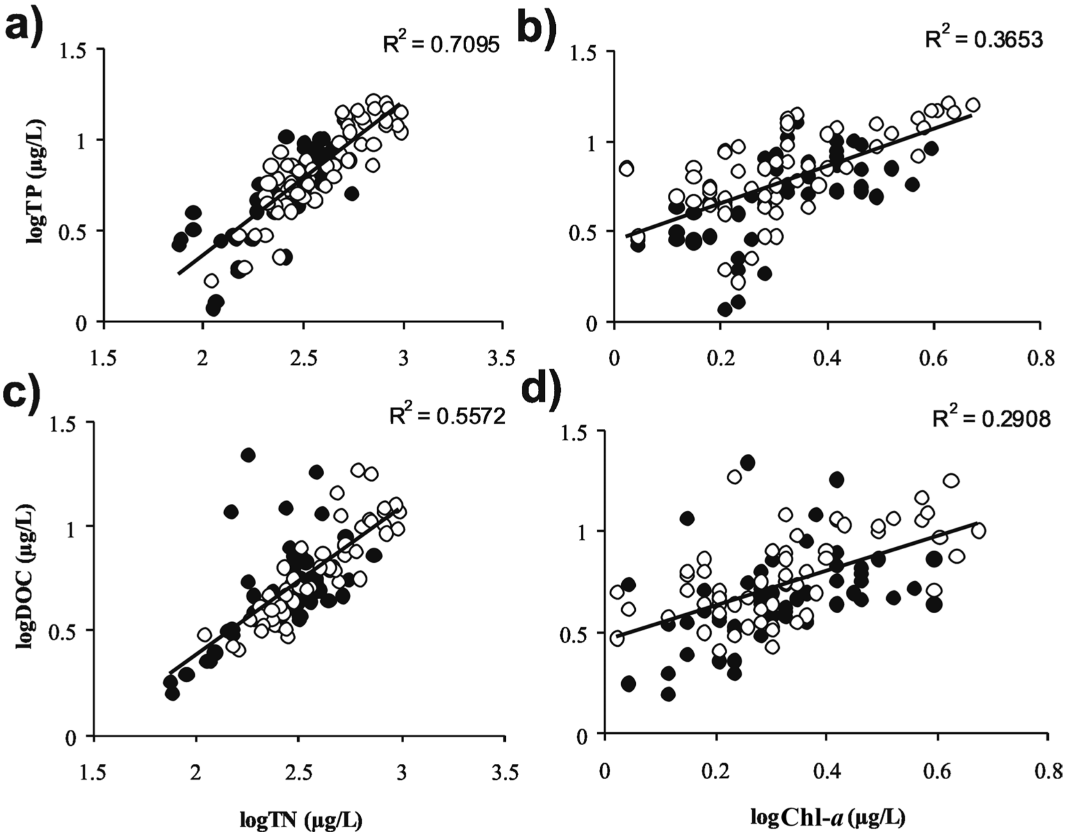

Fig. 6. Relationships between selected environmental variables for lakes (solid circles) and ponds (open circles).

The differences in regional limnology of lakes and ponds could be influenced by the composition of the underlying lake sediments and input catchment areas. For example, Arctic ponds are often alkaline due to the presence of calcareous glacial tills overlying Precambrian bedrock (Douglas et al. 2000, Hamilton et al. 2001). Westover et al. (2009) found that the main difference in limnology between lakes and ponds from the mainland Kitikmeot region and Victoria Island lakes was based on the solubility of elements in sediments, indicated by the dominance of Ca and Mg cations from dolomitic sediments characteristic of Victoria Island lakes, and Na for lakes throughout the marine sediment deposits characteristic of the mainland Kitikmeot region. In contrast, the tree-line, central, and Baffin regions all contained a relative cationic abundance of Ca > Na > Mg > K, which reflects the relative solubility of silicate minerals from the igneous sources of the sediments in these areas (Wetzel 2001). Lakes and ponds in the coastally influenced western Hudson Bay region contained higher concentrations of sodium (Na > Ca > Mg > K), and subsequently high conductivity, than other regions.

Pienitz et al. (1997) found that coastal lakes had higher concentrations of Na and Cl, and that marine aerosols can strongly influence the chemistry of coastal lakes. While 8 lakes and ponds in our dataset from the western Hudson Bay region were within 2 km of the coast, the majority were 10–100 km from the current coastline. However, this region was inundated by seawater after the retreat of the last glaciation, and many lakes and ponds in this region were isolated from marine environments by the slow isostatic uplift that has continued over the last 7500 years (Pielou 1992). This is reflected by the large glaciomarine sediment composition in this area. Likewise, some lakes within this region are underlain by Achaean metamorphic rock, which can provide a significant source of sodium from feldspar weathering (Banks et al. 1998). As a result, the limnology of these systems is likely influenced by the legacy marine sediments in the surficial geology of the western Hudson Bay region.

Local characteristics

Across all sampling locations within our dataset, there were large differences in depth, elevation, and surface area within each region. The influence of these physical characteristics is most pronounced in the limnology of ponds (<2 m depth) versus lakes (Fig. 4), especially in the western Hudson Bay region where the concentration of Fe and the conductivity of ponds was significantly higher

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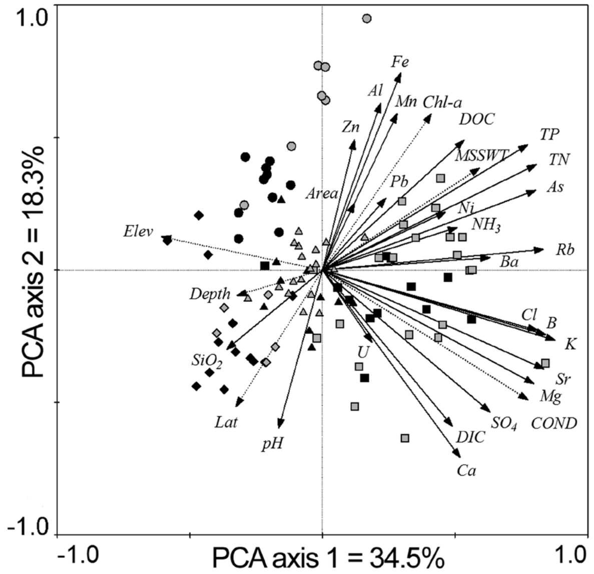

Fig. 7. Principal components analysis of significant environmental indicators (including metals) for the 97 sampling locations. Sites and variables are classified as in Fig 2.

than lakes (Fig. 2). Higher inputs to lakes and ponds were found in low relief regions, but the relationship between the surface area of a lake or pond and its limnological characteristics is not clear. Hamilton et al. (2001) found that larger lakes had a low concentration of ions, nutrients, and carbon particulates, but our dataset did not indicate similar relationships with surface area, likely due to the low topographic relief of the majority of our sampling locations across mainland Nunavut. The lakes in the southwestern Hudson Bay region (Fig. 1b) are characterized by large surface areas with a relatively shallow maximum depth (median depth 4 m). These shallow, large, and wind-swept systems have higher concentrations of ions, higher productivity, and higher nutrients (Fig. 4), which could be due to increased interaction with organic-rich benthic sediments or because of wind-induced sediment resuspension (Larsen and MacDonald 1993).

Intra-regional PCAs displayed many similar patterns to those observed across physiogeographic regions (Fig. 5). In each region, the main differences observed were the separation of lake and pond samples into opposite quadrats. There was a gradient of decreasing nutrient concentrations and Chl-*a*, along a latitudinal gradient, especially in pond systems. This is likely due to the influence of higher nutrients on productivity among more southern sites as well as the smaller volume of pond systems resulting in higher turnover, remobilization of particles from the sediments, and the reduced water residency time in these bodies. Pond systems are generally smaller, hydrologically disconnected systems that can also be influenced by the concentration of elements during drought and dilution during large precipitation events (Macrae et al. 2006). In addition, temperature and nutrient concentrations were often the largest gradients within each region and may be reflective of large differences in local landscape variables that influence a system's temperature, such as depth, surface area, and elevation (Fig. 5).

Key relationships

Although regionality and local characteristics were important components in determining the limnology of lakes and ponds, several key relationships between DOC, TP, TN, and to some extent Chl-*a*, were common across all regions (Fig. 6). A large portion of nutrient inputs to Arctic soils occurs from precipitation, while limited nitrogen fixation by microbial and algal communities is temperature linked (Chapin 1983). The high TN:TP ratios found indicate phosphorus limitation for both lake and pond systems across all regions, and the majority of nitrogen inputs likely occur from allochthonous sources. The prevalence of phosphorus limitation in Canadian Arctic aquatic systems is consistent with other limnological surveys (Gregory-Eaves et al. 2000, Hamilton et al. 2001, Lim et al. 2001, Michelutti et al. 2002, Rühland et al. 2003, Westover et al. 2009). The highest concentrations of both phosphorus (Fig. 4i) and nitrogen (Fig. 4j) were in lakes and ponds in the southern Hudson Bay region, but similarly high concentrations were also found in lakes and ponds in several regions in systems that had higher MSSWT (Fig. 5). The significant relationship found in our results between nitrogen and temperature (Table 3) strongly suggests that nitrogen concentrations may be dependant on temperature; areas with higher mean temperatures may have increased microbial decomposition, larger amounts of vegetation, and high allochthonous inputs that correspond to higher nitrogen concentrations found. This is consistent with Hobara et al. (2006) who found that nitrogen fixation was several times greater than decomposition rates and exponentially increased under higher temperature, moisture, and light availability. The short growing season, low temperatures, and limitations in available phosphorus and nitrogen are known to significantly reduce primary production in Arctic lakes and ponds (Schindler et al. 1974, Alexander et al. 1989).

Although organic inputs from terrestrial sources and internal biogeochemical processing may be significant, rates of organic matter decomposition in Arctic soils are lower than similar temperate systems due to lower temperatures and subsequently lower rates of autochthonous inputs (Hobbie 1973). The overall concentrations of DOC in our dataset were low compared to temperate systems, but higher concentrations of DOC were found in lakes and ponds with higher corresponding MSSWT (Table 3), likely reflecting greater terrestrial inputs of available dissolved organic matter during a warmer and more prolonged ice-free season. Concentrations of nutrients were also found to be significantly higher in samples from ponds in the Hudson Bay region, and significantly correlated to systems that contained higher concentrations of DOC (Table 3; Fig. 4), likely reflecting higher, temperature-mediated, microbial activity within these systems. This is consistent with Kling (1995), who identified that bacterial respiration and production is strongly linked to inputs of labile dissolved organic matter in Lake Toolik, Alaska.

Biological productivity within freshwater systems is also highly influenced by temperature, nutrients, and organic carbon inputs (Rouse et al. 1997). Median concentrations of Chl-*a* for the central and Baffin regions (0.9 and 0.7 $\mu g\ L^{-1}$, respectively) were comparable to values in the eastern Northwest Territory (0 9 $\mu g.L^{-1}$; Pienitz et al. 1997), the central-east tree-line areas of the Northwest Territory and central-west region of Nunavut (0.85 $\mu g\ L^{-1}$; Rühland et al. 2003), and in the northwestern Kitikmeot region of Nunavut (0.60 $\mu g.L^{-1}$; Westover et al. 2009). Chl-*a* was also significantly correlated to both phosphorus and nitrogen, indicating a primary nutrient limitation within lakes and ponds in our dataset (Fig. 6). In addition, Chl-*a* was found to be significantly correlated ($r = 0.62$, $p < 0.05$) with Fe in lakes. Dillon and Molot (1997) noted that nutrient inputs to temperate lakes and ponds are organically bound, which is often reflected in significant DOC–TP and DOC–TN correlations (Table 3; Dillon et al. 1991, Dillon and Molot 1997). Iron enhances phosphorus complexation with DOC and can increase catchment fluxes of TP (Jones et al. 1988, Dillon and Molot 1997). Internal recycling of phosphorus and iron also depends on the depth of the system, where shallow large lakes will have a higher potential for release of nutrients and other compounds from sediment due to wind-induced resuspension.

The input of organic carbon to Arctic lakes and ponds greatly influences the limnology and productivity of these systems. For the 99 samples with POC data available, only 6 had POC:Chl-*a* values <200:1, reflecting the relatively large input of allochthonous carbon sources. The median ratio of 548:1 is similar to other Arctic limnology surveys (e.g., Hamilton et al. 2001, Lim et al. 2001, Michelutti et al. 2002), and is generally representative of low-productivity systems north of the tree-line. In addition, Secchi depth was almost always equal to the maximum observed depth at all of our mid-basin sampling locations, indicating the overall clarity of aquatic tundra systems and low concentrations of POC. Those systems with higher available concentrations of nutrients, and subsequent higher productivity, had higher concentrations of DOC. This is also likely due to inputs from the extensive wetlands in the southern regions of Hudson Bay, which are a key contributor of allochthonous sources of DOC (Wetzel 1992). The concentration of the more abundant metals (Fe, Al, Mn, and Rb) were also positively associated with particulates (POC, PON), indicating likely allochthonous inputs (Hamilton et al. 2001). In addition, Arctic lakes and ponds are primarily highly oxidizing environments where low temperatures, low autochthonous organic matter input, and low sediment accretion leads to conditions where relatively high retention of diffusing Mn and Fe in sediments occurs (Cornwell and Kipphut 1992).

The pH of freshwater systems is an important component of the sediment–water interface because it controls metal cation hydrolysis and specific sorption rates. Under alkaline conditions, sediments sorb Al and Zn, while Cu, Fe, and Mn precipitate (Jackson 1998); however, no correlations were found between pH and the concentrations of Fe or Mn regardless of alkaline conditions (Table 3). Hobbie (1973) indicated that high Fe inputs are primarily controlled by chelation with available organic acids that keep iron in the water column. Molot and Dillon (2005) showed that the loss of Fe was negatively correlated with DOC. High concentrations of Fe found in lakes sampled in the tree-line region suggest higher inputs from terrestrial organic matter sources. In addition, pond systems had a stronger relationship between DOC and Fe than lake systems ($r = 0.62$ vs. 0.43), possibly due to the resuspension of Fe from wind-induced mixing that is common in ponds (Schlesinger 1997).

Concentrations of Sr and Rb were correlated to several ions (Ca, Mg, K, Cl, and SO_4), nutrients, and temperature. Rb in particular was strongly correlated to temperature, particulates, K, nutrients, and Chl-*a* (Table 3). The correlation with K may be due to competitive uptake with K by terrestrial vegetation (Murphy et al. 1955, Drobner and Tyler 1998). In addition, both Rb and K are found in higher concentrations in clay particulates because clay soils have a high affinity for both Rb and K (MacDougall and Harris 1969, Drobner and Tyler 1998). Sr concentration was found to be elevated in lakes with high concentrations of Ca and Ba, and all 3 of these elements had significant positive correlations to DIC (Table 3). This is consistent with Puznicki (1996), who reported high concentrations of Ba and Sr in lakes with calcium carbonate-rich deposits in the central Northwest Territory.

Conclusion

The review of 113 lakes and ponds from multiple areas across a large spatial extent of the eastern Canadian Arctic indicated that the limnology of the system primarily reflected differing geologic and landscape patterns at the regional scale. For example, lakes and ponds in the western Hudson Bay region shared common patterns in

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conductivity, DIC–DOC, temperature, and nutrients. These regional characteristics are likely due to the glaciomarine origin of sediments. In contrast, the tree-line region was characterized by lower concentrations of major ions and higher productivity than other regions.

Our dataset reflects lakes sampled across a large spatial extent, and several significant gradients were found across all regions. The relationships found between nutrients (TP, TN) and productivity (Chl-*a*) was similar to other Arctic limnology reviews, but the concentrations of nutrients and Chl-*a* were higher in our dataset, especially in the southern regions of Nunavut. In addition, nitrogen concentrations were found to be strongly correlated to mid-summer surface water temperature across all regions. High TN:TP ratios indicated that phosphorus limitation was prevalent in both lakes and ponds across all regions. Although strong regional gradients were observed, there were significant localized gradients in nutrients, major ions, and temperature due to local landscape specific conditions, especially depth. Shallow pond systems had a much higher variability in the concentration of major ions and metal concentrations than that of deeper lake systems, especially in the western Hudson Bay region. The overall general patterns in limnological characteristics within each region, however, were similar for both lakes and ponds. Thus, anticipated future changes in climate may influence both lakes and ponds in a similar fashion within a particular region.

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