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Limnological Characteristics of a High Arctic Oasis and Comparisons across Northern Ellesmere Island

BRONWYN E. KEATLEY,[1,2] MARIANNE S.V. DOUGLAS[3] and JOHN P. SMOL[1,2]

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ABSTRACT. Rapidly warming temperatures in the Arctic are predicted to markedly alter the limnology of tundra lakes and ponds. These changes include increases in aquatic production, pH, specific conductivity, and nutrient levels. However, baseline limnological data from High Arctic regions are typically restricted to single sampling events or to repeated samplings of a few select sites, which limits our ability to assess the influence of climatic change. We employ two techniques to examine the influence of a warmer climate on High Arctic aquatic ecosystems. First, we compare limnological characteristics in July 2003 of 23 ponds and lakes from an atypically warm High Arctic oasis on Ellesmere Island to those of 32 ponds and lakes located across northern Ellesmere Island, where climatic conditions are much cooler and more typical of High Arctic environments. Second, we resample 13 sites originally analyzed in 1963 to assess the influence that 40 years of rising temperatures (as documented by meteorological records) have had on the limnological characteristics of these freshwater ecosystems. The specific conductivity values, as well as the concentrations of nutrients and related variables (especially dissolved organic carbon, DOC), from the Arctic oasis sites are among the highest yet reported from the Canadian High Arctic, and they are significantly higher than those from the polar desert around northern Ellesmere Island. Comparison of the modern and historical data indicated that most oasis sites currently have higher pH than they did in 1963, which is consistent with the documented warming of temperatures.

Key words: limnology, polar oasis, lakes, ponds, nutrients, DOC, climate change, Lake Hazen, Ellesmere Island, Canadian High Arctic

RÉSUMÉ. On prévoit que les températures en hausse rapide dans l'Arctique auront pour effet de modifier considérablement la limnologie des lacs et étangs de la toundra. Parmi ces changements, notons l'augmentation de la production aquatique, du pH, de la conductibilité spécifique et des niveaux de nutriments. Toutefois, les données limnologiques de base des régions de l'Extrême-Arctique se limitent typiquement à des événements d'échantillonnage unique ou à des échantillonnages répétés de quelques sites choisis, ce qui a pour effet de restreindre notre aptitude à évaluer l'influence des changements climatiques. Nous avons eu recours à deux techniques pour examiner l'influence d'un climat plus chaud sur les écosystèmes aquatiques de l'Extrême-Arctique. Premièrement, nous comparons les caractéristiques limnologiques de juillet 2003 de 23 lacs et étangs d'oasis atypiquement chaudes de l'Extrême-Arctique sur l'île d'Ellesmere à celles de 32 étangs et lacs parsemés dans le nord de l'île d'Ellesmere, où les conditions climatiques sont beaucoup plus fraîches et plus typiques des milieux de l'Extrême-Arctique. Deuxièmement, nous avons rééchantillonné 13 sites qui avaient d'abord été analysés en 1963 et ce, dans le but d'évaluer l'influence qu'ont eu 40 années de températures à la hausse (d'après les données météorologiques) sur les caractéristiques limnologiques de ces écosystèmes d'eau douce. Les valeurs de conductibilité spécifique, de même que les concentrations en nutriments et les variables connexes (surtout le carbone organique dissous ou COD) des oasis de l'Extrême-Arctique figurent parmi les valeurs les plus élevées signalées dans l'Extrême-Arctique canadien, et sont considérablement plus élevées que celles des déserts polaires du nord de l'île d'Ellesmere. La comparaison des données contemporaines aux données historiques laisse entrevoir que la plupart des oasis ont un pH plus élevé actuellement qu'en 1963, ce qui coïncide avec la constatation documentée de l'augmentation des températures.

Mots clés : limnologie, oasis polaire, lacs, étangs, substances nutritives, COD, changement climatique, lac Hazen, île d'Ellesmere, Extrême-Arctique canadien

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[1] Paleoecological and Environmental Assessment and Research Lab (PEARL), Department of Biology, Queen's University, 116 Barrie Street, Kingston, Ontario K7L 3N6, Canada
[2] Corresponding authors: bronwynkeatley@gmail.com or smolj@biology.queensu.ca
[3] Paleoenvironmental Assessment Laboratory (PAL), Department of Geology, University of Toronto, 22 Russell Street, Toronto, Ontario M5S 3B1, Canada; present address: Canadian Circumpolar Institute, University of Alberta, Campus Tower, 8625–112 Street, Edmonton, Alberta T6G 0H1, Canada

INTRODUCTION

The Canadian High Arctic is broadly classified as a polar desert because of its limited precipitation and harsh annual climate (Muc and Bliss, 1977). Given the vastness of the High Arctic landscape, however, it is not surprising that its climate is heterogeneous. Arctic oases, regions of great biological production and diversity, are associated with greater availability of local water sources compared to the surrounding polar desert and are generally found at small scales (often less than 5 km^2; Edlund and Alt, 1989). In the Canadian High Arctic, oases have been identified on Devon Island, including Truelove Lowland (Bliss, 1977a), and on Ellesmere Island, including Eureka, Tanquary Fiord, and Lake Hazen (Edlund and Alt, 1989) and Alexandra Fiord (Freedman et al., 1994). Similar areas occur at Polar Bear Pass on Bathurst Island, at Sherard Bay on Melville Island, and at Mould Bay on Prince Patrick Island (Aiken et al., 1999 onwards). However, even among Arctic oases, the oasis of our study area at Lake Hazen is strikingly warm and lush, particularly given its extreme location north of latitude 80˚ N.

Arctic oases are of particular interest to ecologists examining the effects of recent climatic changes because they represent a glimpse of what the more typical polar desert ecosystems might become under a warmer climate. By assessing the biological, physical, and chemical processes occurring in Arctic oases, we may better recognize the effects of climate change in other Arctic regions. Because of their ecological importance and their uniqueness in the High Arctic, polar oases have been relatively well studied compared to their polar desert counterparts. For example, terrestrial faunal surveys (Bliss, 1977b; France, 1993) and botanical surveys (Muc and Bliss, 1977; Soper and Powell, 1985; Henry et al., 1990) have been reported from Lake Hazen, Truelove Lowland, and Alexandra Fiord (botanical only). However, aquatic biological research from Arctic oases has largely been limited to a few lakes in the Lake Hazen area (zooplankton, McLaren, 1964; non-diatom algae, Croasdale, 1973; cyanobacteria, Quesada et al., 1999) and to three lakes at Truelove Lowland (Minns, 1977).

While Arctic oases are largely defined as regions of greater biological production and diversity, little is known about the baseline limnological conditions that characterize lakes and ponds from these regions. For example, limited limnological investigations were undertaken on Truelove Lowland (Minns, 1977), and across northern Ellesmere Island (Hamilton et al., 1994, 2001), which included some sites in the oasis at Lake Hazen. More recent aquatic work on dissolved organic carbon (DOC) and ultraviolet (UV) penetration has been conducted on Skeleton Lake in the Hazen oasis (Laurion et al., 1997). Also near Lake Hazen, a physical and chemical limnological survey of ponds and lakes was carried out by Canada's Defence Research Board (DRB) in 1963, with some additional observations in 1964 (Oliver and Corbet, 1966). This valuable data set includes seasonal measurements of important limnological variables such as pH, specific conductivity, and major ions, but does not provide comparison data from aquatic systems at similar latitudes outside of the Arctic oasis zone. Nonetheless, this early 1960s data set provides important reference data that allow us to assess whether these sites have changed over the past ~40 years, a time of documented climate change in northern Ellesmere Island (Environment Canada, 2004).

Excluding the oasis region of Lake Hazen on northern Ellesmere Island, previous limnological survey data are available for aquatic systems near Alert, Ellesmere Island (Antoniades et al., 2003a). Basic limnological data have also been provided for some lakes to the south of Lake Hazen (Smith, 2002). In addition, detailed limnological analyses have been undertaken in complex lakes along the northern coast of Ellesmere Island (Gibson et al., 2002; Van Hove et al., 2006).

Our primary objective in this study is to characterize present-day limnological characteristics of lakes and ponds on northern Ellesmere Island, including a large number of sites located within a warm oasis region. Warm conditions have been linked to reduced ice cover, longer growing seasons, higher pH and conductivity, and enhanced biological production (e.g., Douglas and Smol, 1999; Antoniades et al., 2005; Smol et al., 2005). However, these hypotheses have not yet been tested from sites located on similar bedrock and at comparable latitudes. Hence our goals are threefold: 1) to provide baseline limnological data from sites located across northern Ellesmere Island, both within and outside an Arctic oasis, and to compare these to other Arctic regions; 2) to examine the hypothesis that oasis sites will have limnological characteristics different from those of sites located outside the oasis; and 3) to assess differences between water chemistry data from 1963 and 2003 for selected oasis sites.

METHODS

Site Description

Our sampling took place on northern Ellesmere Island, largely, but not exclusively, within Quttinirpaaq National Park (Fig. 1). Three physiographic regions exist within the Park: the Grant Land Mountains, which cover 65% of the Park in the north; the Lake Hazen Basin surrounding Lake Hazen; and the Hazen Plateau, which is located between Lake Hazen and the southern edge of Quttinirpaaq National Park (Bednarski, 1994). Four climatic zones can also be delineated within the Park: 1) a cool marine climate in the northern coastal areas, 2) very cool regions characterized by high-elevation ice caps, 3) a marine climate in the southeastern portion, and 4) a continental climate at Lake Hazen and Tanquary Fiord (Thompson, 1994). The north coast receives the most precipitation, and the areas near Lake Hazen, the least (Thompson, 1994).

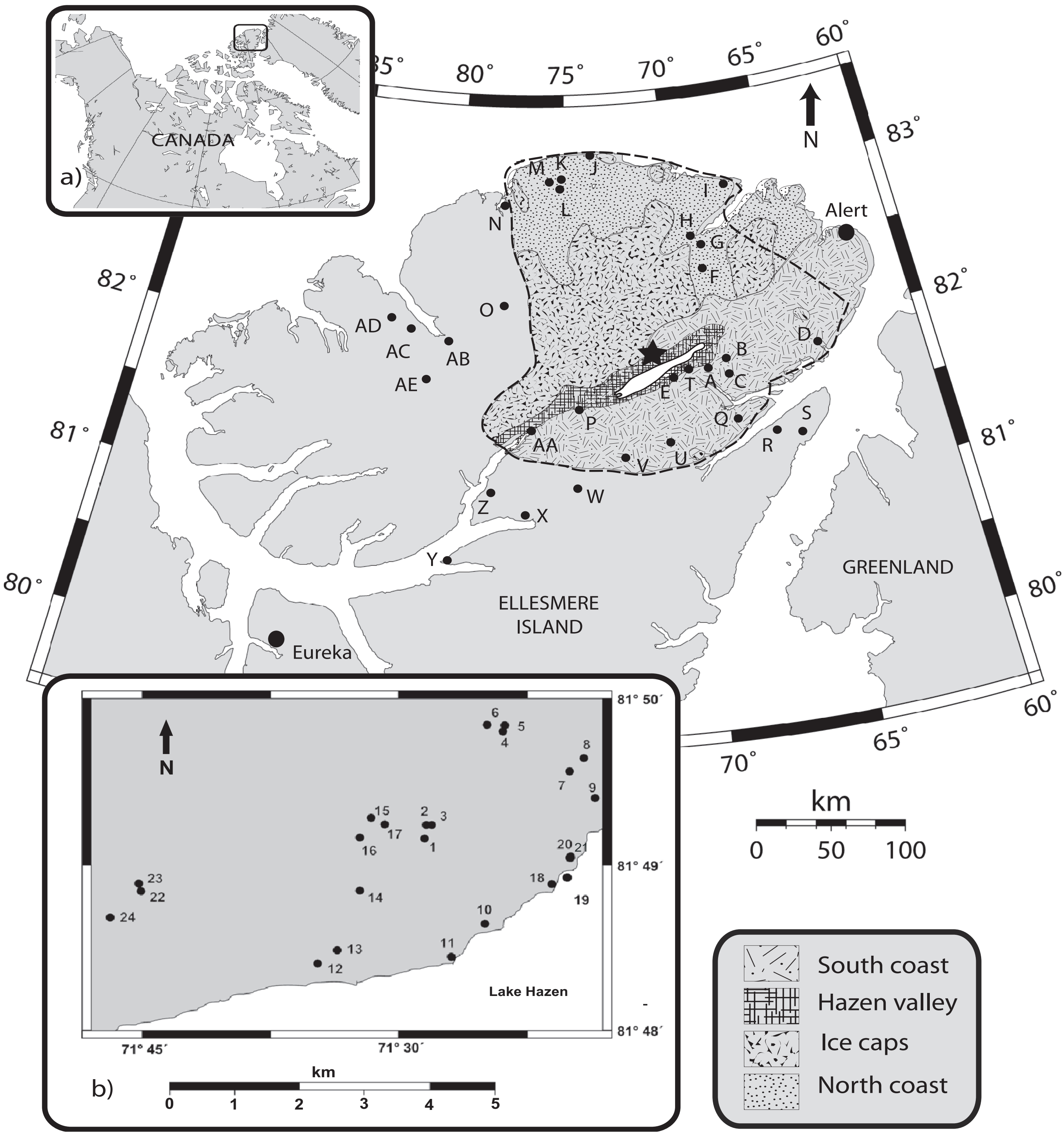

FIG. 1. Location map of northern Ellesmere Island. Inset a) indicates Ellesmere Island within Canada. The main map shows the northern sites around Ellesmere Island. The dashed black line denotes the boundary of Quttinirpaaq National Park and the patterned areas within this boundary represent different climate regions based on Thompson (1994). The black star indicates the location of the oasis sites detailed in inset b). Inset b) details the oasis sites just north of Lake Hazen.

The Hazen Basin region experiences anomalously warm summer conditions because of its continental location and its placement on the leeward side of the Grant Land Mountains (Gray, 1994). While average July daily temperatures (1971–2000 averages) are 5.7˚C at Eureka and 3.3˚C at Alert (Environment Canada, 2004), temperatures at the Lake Hazen camp during our field work in July 2003 reached an average daily maximum of 16˚C, with a minimum as high as 9.6˚C. Average annual precipitation is 75.5 mm at Eureka (1971–2000) and153.8 mm at Alert (Environment Canada, 2004). The summer melt periods are shortest (~3 weeks) for the north coast, while they last

~8 weeks near Alert and ~10 weeks at Lake Hazen (Thompson, 1994).

When defined by bioclimatic zone, the Lake Hazen region falls in Zone 4 (Edlund and Alt, 1989), the most diverse botanical region in the High Arctic. It is dominated by shrubs and sedges, and its vegetation includes more than 100 species that are typical of more southerly Arctic locations (Edlund and Alt, 1989). Within the Lake Hazen oasis, however, there are also some mountain sites that we consider "controls" because of their relatively high elevation and lack of catchment vegetation. Outside the oasis, study sites are located within a broad range of vegetation zones, from low-diversity Zone 0 sites (unvegetated) to Zone 3 sites (60–100 taxa, prostrate shrub zone, dominated by *Salix arctica* or *Dryas integrifolia* or both; Edlund and Alt, 1989).

Geology

Northern Ellesmere Island is largely underlain by sandstones, limestones, and slates (Christie, 1957, 1964). In the most northerly regions along the north coast, Precambrian gneisses, schists, and granitic rock dominate, while volcanic and sedimentary rocks, including sandstones and limestones, underlie the northern interior regions (Christie, 1964). The north shore of Lake Hazen, including the Hazen oasis, is composed of Permian, Triassic, Jura-Cretaceous, and Cenozoic sandstone and shale (Christie, 1964).

Sampling Techniques

In July 2003, 55 ponds (< 2 m deep) and lakes (> 2 m deep) were sampled around northern Ellesmere Island (Fig. 1). Of these, 23 sites were located in the Arctic oasis immediately north of Lake Hazen. These are hereafter referred to as "oasis sites" and given unofficial names EP1 through EP24. It should be noted that EP19 is Lake Hazen, and is kept separate from all analyses because of its very large size (i.e., surface area ~54 200 ha). Three of these sites (EP22, 23, 24) were located at relatively high elevations of over 850 m above sea level. Therefore, despite their location in the warm oasis region, they serve as cooler controls within the oasis set. The remaining 31 sites were selected from around the northern half of Ellesmere Island, to the north, east, south, and west of Lake Hazen. These are hereafter referred to as "northern sites" and given unofficial names EPA through EPAE).

For each site, latitude, longitude, and elevation measurements were taken using either the helicopter global positioning unit and an altimeter or a handheld global positioning unit and topographic maps. Water temperature was recorded with a hand-held thermometer, and samples for total phosphorus (unfiltered, TPu), trace metals (aluminum, Al; beryllium, Be; cadmium, Cd; chromium, Cr; cobalt, Co; copper, Cu; iron, Fe; lead, Pb;, manganese, Mn; molybdenum, Mo; nickel, Ni; vanadium, V; zinc, Zn; and silver, Ag), and major ions (calcium, Ca; magnesium, Mg; sodium, Na; potassium, K; chloride, Cl; sulphate SO_4) were retrieved, using pre-cleaned 125 mL sample bottles, from ~15 cm depth within the nearshore area of each site. We used sampling techniques and analyses identical to those of our previous limnological investigations, as well as a similar time frame, which allows us to make comparisons among regions (Douglas and Smol, 1994; Lim et al., 2001; Michelutti et al., 2002a, b; Lim and Douglas, 2003; Antoniades et al., 2003a, b; Lim et al., 2005).

Additional water samples for pH, specific conductivity, filtered nutrients and related variables (dissolved silica, SiO_2; total phosphorus filtered, TPf; soluble reactive phosphorus, SRP; nitrate, NO_3; nitrate-nitrite, NO_3NO_2; ammonia, NH^3; total Kjeldahl nitrogen, TKN; total dissolved nitrogen, TdN; particulate nitrogen, PON; dissolved organic carbon, DOC; dissolved inorganic carbon, DIC; particulate organic carbon, POC; and chlorophyll *a*, Chl*a*) were taken with 1 L plastic Nalgene® bottles, rinsed three times with pond/lake water. At base camp, pH and specific conductivity were measured the same day the samples were obtained, using a handheld Hanna pHep 3 meter and a YSI model 33 conductivity meter, respectively. The dissolved and particulate fractions of the variables described above were filtered on site following guidelines in Environment Canada (1994). All other analyses were performed at the National Water Research Institute (NWRI) in Burlington, Ontario (Environment Canada), using protocols described in Environment Canada (1994).

Statistical Analyses

Data were visually screened to assess normality of distribution using CALIBRATE 1.0 (Juggins and ter Braak, 1992). Any variables that were not normally distributed were transformed using mostly $\log_X$, $\log_X + 1$ or square root transformations. Variables whose distributions could not be normalized were run passively in statistical analyses (i.e., they were plotted onto the biplot after it was produced, and thus did not affect the results). A Pearson correlation matrix with Bonferroni-adjusted probabilities was performed on the full data set to remove those variables that were highly correlated with each other, thereby reducing the data set to a more manageable size for ordination analyses.

A Principal Components Analysis (PCA) was run on the reduced data set (by removing highly correlated variables) to assess the important limnological gradients in the data set, using the ordination program CANOCO 4.5 (ter Braak and Šmilauer, 2002).

Canonical Variates Analysis (CVA, also known as linear discriminant analysis), was used to identify environmental variables that significantly discriminate between clusters of samples (in this case, our oasis and northern sites) (Lepš and Šmilauer, 2003). Initially, a CVA was run for each individual variable to assess whether it explained a significant portion of the variation distinguishing the two groups. Any significant variables were retained. With the same variables used for the PCA, we performed another

CVA with forward selection to choose, in sequence, the most important explanatory variables.

Comparison to Historical Data

The DRB water sampling of sites around Lake Hazen (Oliver and Corbet, 1966), provides the earliest historical limnological survey data available in the Canadian High Arctic, and thus provides a unique opportunity to assess changes in water chemistry on a regional scale over 40 years. We used site descriptions and locations from the DRB map to identify a subset of sites common to both our study and the DRB study. While we acknowledge that differences in both measurement techniques and seasonal sampling dates make direct comparisons of pH, specific conductivity, and major ion concentrations difficult, we nonetheless make use of this valuable historical data set.

RESULTS AND DISCUSSION

Physical Characteristics

The oasis sites consisted of 19 ponds and four small lakes (EP1, EP2, EP3, EP24; median surface area $(SA)_{oasis}$ = 0.13 hectares). In contrast, less than one-third of the northern sites were ponds (9 out of 31, median $SA_{northern}$ = 6 hectares). As would be expected from their location in the oasis and their smaller sizes, the oasis sites were much warmer (mean temp. = 15.7˚C) than the northern sites (mean temp. = 9.1˚C). The difference in elevation between the two groups was not significant ($mean_{oasis}$ = 318 m, $mean_{northern}$ = 289 m).

pH, Specific Conductivity, and Major Ions

The oasis and northern sites were not significantly different with respect to pH values ($mean_{oasis}$ = 8.23, $mean_{northern}$ = 8.20, Tables 1 and 2), and their mean pH values were similar to values measured elsewhere in the Canadian Arctic, including Devon Island (Lim and Douglas, 2003) and Bathurst Island (Lim et al., 2001), as well as Alert, Ellesmere Island (Antoniades et al., 2003a). The similar pH both between our two groups of sites and between our study and previous surveys (Lim et al., 2001; Antoniades et al., 2003a; Lim and Douglas, 2003) likely reflects the broadly similar bedrock common to most of the sites.

Specific conductivity was significantly higher in the oasis sites (mean = 490 µS/cm) than in the northern sites (mean = 245 µS/cm) ($p = 0.022$, Tables 1 and 2). Previous High Arctic limnological surveys have reported mean specific conductivity ranging from ~100 µS/cm (Victoria Island, Michelutti et al., 2002a; Bathurst Island, Lim and Douglas, 2003) to up to 405 µS/cm (Ellef Ringnes Island, Antoniades et al., 2003b), although specific conductivities over 300 µS/cm generally reflect the influence of sea spray on coastal lakes and ponds (Michelutti et al., 2002b; Antoniades et al., 2003b). While some of our northern sites include coastal ponds, all our oasis sites are located inland; thus, sea spray cannot be a factor for these elevated specific conductivity values. In some sites, very high SO_4 values contribute to high conductivity in both the oasis (EP9, a very shallow site) and the northern (EPY, a small coastal site with gypsum precipitates) data sets (Tables 1 and 2). Both these sites also had high Ca concentrations, suggesting that local bedrock may have been important in influencing these values, as Ca and SO_4 are known to have very high concentrations in gypsiferous shale (McNeely et al., 1979).

Higher specific conductivities would also be expected, however, in smaller water bodies under warmer conditions, as increased evaporation would increase the concentration of solutes in the water column. During the summer months, prolonged solar radiation, combined with the clear skies and warm temperatures characteristic of the Lake Hazen basin, could result in enhanced evaporation, further concentrating the solutes within the lakes and ponds. Although we do not have seasonal data from our field season, previous work at Lake Hazen documented an average drop in water levels of ~0.4 cm/day throughout the ice-free season (Oliver and Corbet, 1966). This appears to be the case in our oasis sites; indeed, the subset of cool, poorly vegetated, high-elevation sites within the oasis region (EP22, 23, 24) had much lower conductivities (mean = 84 µS/cm) than the remaining, low-elevation oasis sites.

Concentrations of major ions (Ca, K, Mg, Na, SO_4) were typically greater in oasis sites, and K concentrations were significantly higher ($mean_{oasis}$ = 7.0 mg/L, $mean_{northern}$ = 1.6 mg/L). Average K concentrations elsewhere in the High Arctic range from 0.24 mg/L (Victoria Island; Michelutti et al., 2002a) to 4.6 mg/L (Axel Heiberg Island; Michelutti et al., 2002b). Non–marine derived K is often associated with exudates from plants (Prentki et al., 1980). As previously discussed, the inland location of the oasis points to a terrestrial source of K; thus, the relatively high concentrations of K are likely indicative of the more highly vegetated catchments common in the oasis. Indeed, our high-elevation sites were distinctive in that they had an average K concentration of 0.48 mg/L, less than 6% of that found in the oasis sites. More specifically, Na:K ratios less than 2:1 may reflect enhanced terrestrial production (McNeely et al., 1979). Therefore, the low ratio of Na to K in the oasis sites ($Na{:}K_{oasis}$ = 1.5, $Na{:}K_{northern}$ = 3.8) is likely indicative of the more developed catchment vegetation. Once again, our high-elevation oasis sites had relatively higher Na:K (1.9) than the other oasis sites, reflecting the sparseness of catchment vegetation. Average Na:K ratios previously reported from across the Canadian Arctic range from 1.8 (Victoria Island; Michelutti et al., 2002a) to 18.4 (Alert; Antoniades et al., 2003a).

Nutrients and Related Variables

As expected, nutrients (TPu, TPf, SRP, TdN, TKN) and related variables (DOC, POC, PON, SiO_2) were significantly

TABLE 1. Summary of selected limnological variables for the northern sites and Lake Hazen. Lake Hazen is isolated at the bottom because of its extremely large size. All sites were sampled in July 2003, and specific days are given in the "Date" column. Full details for other limnological parameters (e.g., metals, rare earth elements) are available in Keatley (2007). Lakes ("L") are defined as being over 2 m deep and ponds as under 2 m. Three sites for which we were unable to estimate depth are denoted as "L?". Non-standard abbreviations are as follows: elevation (elev, given in meters above sea level) and surface area (SA). Abbreviations for other parameters are given in the text.

ID	Name	Lat. N	Long. W	Date	Elev (m)	SA (ha)	Pond/ Lake	pH	Cond µS/cm	Chl*a* µg/L	DOC mg/L	DIC mg/L	POC mg/L	PON mg/L	NH_3 mg/L	TKN mg/L
EPA	Craig	81°50.34'	68°51.13'	12	152	1455.0	L	8.47	296	0.05	3.1	31.4	0.204	0.030	0.016	0.179
EPB	Appleby	81°50.90'	68°15.49'	12	366	48.8	L	8.23	232	0.05	4.7	36.3	0.246	0.030	0.021	0.383
EPC	Brainard	81°45.81'	68°10.32'	12	640	18.0	L	8.03	169	0.1	3.6	27.4	0.256	0.030	0.021	0.315
EPD		81°46.78'	64°32.96'	12	274	49.1	L?	8.37	172	0.7	3.3	24.4	0.231	0.029	0.036	0.287
EPE		81°42.84'	70°05.33'	12	259	1.1	P	9.00	379	0.6	12.6	47.2	0.509	0.047	0.031	0.774
EPF		82°25.20'	68°12.77'	12	91	125.0	L	8.13	110	0.1	1.5	7	0.208	0.024	0.013	0.044
EPG		82°36.21'	68°12.25'	12	91	14.7	L	8.20	122	0.1	0.8	14	0.403	0.039	0.008	0.054
EPH		82°36.23'	68°13.03'	12	91	0.4	P	8.63	322	0.6	5.9	23.5	0.438	0.050	0.043	0.467
EPI		82°55.11'	66°51.88'	12	15	2.4	P	8.53	75	0.7	2.6	10.8	0.389	0.052	0.008	0.133
EPJ	Ward Hunt	83°05.30'	74°09.87'	13	61	35.0	L	8.30	45	0.6	1	4.4	0.163	0.017	0.067	0.148
EPK	Lake A	83°00.74'	75°23.28'	13	30	490.0	L	7.90	69	0.6	1.3	3.6	0.180	0.027	0.016	0.078
EPL		82°58.60'	75°24.70'	13	46	99.0	L	8.27	56	0.6	1.4	8.5	0.187	0.026	0.044	0.208
EPM		82°58.54'	75°11.44'	13	213	0.3	P	8.63	102	1	4.3	16.1	0.345	0.042	0.040	0.378
EPN	Lake C2	82°49.59'	77°56.24'	13	30	165.0	L	7.73	30	0.6	2.4	2.8	0.145	0.021	0.008	0.049
EPO		82°16.00'	77°53.32'	13	1006	6.3	L	7.47	45	0.5	0.7	3.2	0.083	0.016	0.027	0.065
EPP		81°36.17'	73°53.11'	13	686	6.0	L?	8.17	102	1.4	4.7	11.9	0.415	0.043	0.023	0.398
EPQ		81°27.28'	67°22.21'	17	579	2.4	P	8.87	138	0.7	12.3	24.4	1.670	0.137	0.048	0.997
EPR		81°18.71'	65°34.92'	17	183	14.7	L	8.30	118	0.05	1.1	17.9	0.357	0.021	0.007	0.056
EPS		81°19.41'	66°25.08'	17	335	2.6	L	8.33	131	0.5	2.2	21.2	0.285	0.012	< 0.005	0.068
EPT		81°47.53'	70°26.77'	17	457	0.2	P	8.37	135	0.1	0.9	19.5	0.116	0.021	0.005	0.053
EPU	Carolyn	81°17.96'	70°43.48'	17	305	161.0	L	8.30	119	0.6	0.9	19.3	0.324	0.038	0.005	0.040
EPV	Nan	81°13.15'	72°19.46'	17	305	6.7	L	8.77	409	0.1	5	59.5	0.473	0.055	0.020	0.458
EPW		81°04.89'	74°20.67'	17	518	114.0	L	8.30	109	0.05	0.6	14	0.343	0.042	0.030	0.084
EPX		80°55.91'	76°32.69'	17	396	61.4	L	8.30	154	0.05	0.9	25.9	0.288	0.031	0.013	0.091
EPY		80°36.43'	79°42.96'	17	1	0.1	P	8.23	1500	0.2	2.2	15.5	0.611	0.059	0.035	0.234
EPZ		81°00.50'	78°13.03'	17	244	4.1	L	8.47	160	0.05	2.3	26.9	0.230	0.030	0.009	0.174
EPAA	Kettle	81°23.80'	76°47.14'	18	200	7.7	L	8.73	500	0.5	4.8	23.3	0.292	0.042	0.043	0.403
EPAB		81°58.49'	80°04.14'	18	122	0.6	L?	7.90	58	1.6	1.7	4.8	0.221	0.027	0.005	0.080
EPAC		82°05.44'	81°50.39'	18	76	98.2	L	8.20	200	0.1	1	25.4	0.283	0.039	0.005	0.068
EPAD		82°05.79'	82°34.70'	18	75	0.1	P	8.73	325	0.6	4.7	36.5	0.441	0.045	0.015	0.336
EPAE		81°42.78'	82°17.04'	18	808	0.5	P	8.30	1200	1.5	11.5	22.3	0.430	0.043	0.012	0.936
mean					279	96.5		8.20	245	0.5	3.4	20.3	0.347	0.038	0.022	0.259
median					213	7.7		8.30	135	0.5	2.3	19.5	0.288	0.031	0.016	0.174
max					1006	1455.0		9.00	1500	1.6	12.6	59.5	1.670	0.137	0.067	0.997
min					1	0.1		7.47	30	0.05	0.6	2.8	0.083	0.012	< 0.005	0.040
EP19	Lake Hazen	81°49.37'	71°20.18'	15	154	54200	L	7.73	68	0.05	1.1	9	0.156	0.016	0.0025	0.040

higher ($p < 0.05$) in the oasis sites than in the northern sites (Tables 1 and 2). When we compared only the ponds, most nitrogen fractions, as well as DOC and SiO_2, were significantly higher in the oasis. These high concentrations of TP and TdN in the oasis sites indeed suggest that warmer conditions enhance nutrient export from the catchment into the lake or pond. NH_3 and Chl*a* concentrations did not differ significantly between zones.

TPu values for oasis sites ($mean_{oasis}$ = 11.3 mg/L) were most similar to those reported from more southerly locations, including Banks Island (18 µg/L, Lim et al., 2005), Bathurst Island (12.7 µg/L, Lim et al., 2001), and Mould Bay, Prince Patrick Island (16.1 µg/L, Antoniades et al., 2003a), the latter two of which include sites identified by Aiken et al. (1999 onwards) as potential polar oases. Banks Island includes freshwater environments that occur in low, mid, and High Arctic ecozones, and Banks Island itself is one of the lushest islands in the Arctic Archipelago (Lim et al., 2005). These relatively high TPu concentrations for the oasis sites once again are indicative of their shared characteristics with other relatively warm, productive Arctic regions. It should be noted, however, that while TPu concentrations have been reported from Arctic ponds and lakes that are much higher than those we report for the oasis sites (see Lim et al., 2005 for a summary), these have been attributed to sediment re-suspension rather than indicating high production (Antoniades et al., 2003b).

When classified to trophic status based on TPu values (Wetzel, 1983), 48% of the oasis sites were considered mesotrophic (i.e., TPu 10–30 µg/L, Table 2). TPu concentrations of the northern sites ($mean_{northern}$ = 7 µg/L) were more typical of aquatic habitats in the polar desert at Axel Heiberg Island (mean = 4 µg/L, Michelutti et al., 2002b), Victoria Island (mean = 1.3 µg/L, Michelutti et al., 2002a), and the Haughton Crater, Devon Island (mean = 3.7 µg/L, Lim and Douglas, 2003). Only 19% of northern sites were mesotrophic or above (Table 1). The TPu concentrations of the high-elevation oasis sites (mean = 6 µg/L) were, once again, much lower than those of the oasis area as a whole and even lower than the mean of the northern sites.

TABLE 1 *Continued*

ID	TdN mg/L	TN mg/L	TPu µg/L	TPf µg/L	SRP µg/L	SiO_2 mg/L	Ca mg/L	K mg/L	Na mg/L	Mg mg/L	Cl mg/L	SO_4 mg/L	Al µg/L	Fe µg/L	TN:TPU	Na:K
EPA	0.191	0.216	13.7	2.3	0.5	2.61	44.70	2.44	4.28	17.90	2.39	56.20	25.1	56.0	15.77	1.75
EPB	0.361	0.4155	6.7	2.2	0.2	0.37	30.10	3.53	5.34	17.60	3.20	6.31	1.6	12.4	62.01	1.51
EPC	0.327	0.35	7.4	3.3	0.6	0.73	26.50	1.03	1.61	8.16	0.96	5.14	3.0	17.3	47.30	1.56
EPD	0.293	0.3185	19.0	2.9	0.7	1.15	31.10	0.46	3.18	3.89	7.11	1.58	3.7	25.9	16.76	6.91
EPE	0.752	0.826	8.5	5.8	0.8	3.21	19.10	9.75	11.20	46.70	15.10	52.40	7.3	36.1	97.18	1.15
EPF	0.077	0.097	6.3	1.6	1.7	0.49	18.30	0.32	0.69	3.04	1.05	39.70	177.0	374.0	15.40	2.16
EPG	0.095	0.14	2.9	2.1	0.6	0.88	20.50	0.26	0.20	5.76	0.29	20.70	30.3	48.2	48.28	0.77
EPH	0.469	0.5195	10.9	9.8	0.9	2.21	52.90	0.78	0.78	19.60	0.54	120.00	6.9	31.8	47.66	1.00
EPI	0.183	0.233	6.7	2.3	1.9	0.47	12.30	0.11	0.42	3.23	1.00	4.29	2.7	18.9	34.78	3.82
EPJ	0.217	0.187	4.1	3.8	0.7	0.16	5.53	0.07	0.23	0.73	0.50	0.27	3.8	5.8	45.61	3.29
EPK	0.089	0.113	3.2	2.2	0.1	0.21	4.89	0.41	7.83	1.99	14.70	2.86	12.8	23.2	35.31	19.10
EPL	0.178	0.249	4.1	3.0	0.5	0.45	10.30	0.53	8.33	2.91	15.70	4.17	10.6	11.6	60.73	15.72
EPM	0.405	0.4225	10.3	5.1	0.2	1.33	21.80	0.36	0.43	3.05	0.29	3.83	12.2	236.0	41.02	1.19
EPN	0.067	0.0725	7.4	2.2	1.0	0.20	3.21	0.07	0.72	0.69	1.24	1.51	6.9	12.1	9.80	10.29
EPO	0.128	0.134	1.8	1.4	0.1	0.13	4.11	0.07	0.08	1.93	0.15	5.62	8.6	21.8	74.44	1.14
EPP	0.412	0.452	6.5	3.8	0.6	3.96	19.40	0.69	0.92	1.95	1.50	3.72	69.4	528.0	69.54	1.33
EPQ	1.010	1.143	9.5	6.8	1.6	4.80	30.00	0.12	0.52	5.60	0.36	0.30	20.3	486.0	120.32	4.33
EPR	0.064	0.089	2.4	1.6	0.5	0.35	24.30	0.20	1.74	3.95	3.71	2.06	20.0	25.6	37.08	8.70
EPS	0.107	0.118	2.1	1.5	0.5	0.49	28.30	0.17	0.38	4.85	1.22	5.38	13.6	12.7	56.19	2.24
EPT	0.413	0.457	1.0	1.4	0.4	0.61	26.70	0.15	0.83	5.79	3.07	5.95	11.8	6.6	457.00	5.53
EPU	0.057	0.098	2.1	1.0	0.2	1.12	19.90	0.30	0.60	7.44	0.74	3.54	35.2	60.1	46.67	2.00
EPV	0.408	0.522	5.0	3.6	0.6	1.66	25.90	5.34	7.18	57.30	14.20	50.90	6.0	16.8	104.40	1.34
EPW	0.159	0.205	2.5	1.3	0.2	0.57	18.70	0.18	0.16	4.99	0.30	7.50	52.1	90.0	82.00	0.89
EPX	0.103	0.134	2.6	2.2	0.5	1.67	28.40	0.36	0.30	8.94	0.57	3.49	8.4	12.9	51.54	0.83
EPY	0.159	0.2955	33.5	3.7	3.1	3.62	451.00	1.80	17.30	27.90	29.40	1160.00	2.2	4.2	8.82	9.61
EPZ	0.175	0.209	3.4	1.9	0.7	1.36	27.30	0.65	0.76	9.65	1.72	0.77	2.3	27.9	61.47	1.17
EPAA	0.395	0.453	11.7	4.7	0.7	0.18	30.00	8.48	25.60	41.70	32.40	166.00	14.0	45.8	38.72	3.02
EPAB	0.079	0.1095	3.8	1.0	0.6	0.36	6.36	0.16	0.17	0.94	0.17	1.29	4.0	12.9	28.82	1.06
EPAC	0.179	0.231	4.8	1.1	0.4	1.26	33.90	0.48	1.54	12.00	2.06	26.00	26.5	47.9	48.13	3.21
EPAD	0.351	0.439	5.2	3.6	1.1	3.32	38.70	0.68	1.17	27.80	1.03	68.10	73.1	201.0	84.42	1.72
EPAE	0.882	0.985	8.1	8.3	2.5	5.69	248.00	9.97	4.26	76.00	13.20	827.00	18.4	62.2	121.60	0.43
mean	0.283	0.33	7.0	3.1	0.8	1.47	43.94	1.61	3.51	14.00	5.48	85.70	22.3	83.0	66.73	3.83
median	0.183	0.23	5.2	2.3	0.6	0.88	25.90	0.41	0.83	5.76	1.24	5.38	11.8	25.9	48.13	1.75
max	1.010	1.14	33.5	9.8	3.1	5.69	451.00	9.97	25.60	76.00	32.40	1160.00	177.0	528.0	457.00	19.10
min	0.057	0.07	1.0	1.0	0.1	0.13	3.21	0.07	0.08	0.69	0.15	0.27	1.6	4.2	8.82	0.43
EP19	0.060	0.047	2.0	2.1	0.1	0.60	13.30	0.25	0.30	1.38	0.17	6.32	17.5	37.5	23.50	1.20

The Wetzel (1983) TPu classification places the high-elevation northern sites in the ultra-oligotrophic (i.e., TPu < 5 µg/L, EP23, EP24) or oligo-mesotrophic (i.e., TPu 5–10 µg/L, EP22) category.

Likewise, total N (TN) values for the oasis sites ($mean_{oasis}$ = 1.14 mg/L) exceed the previously reported averages for Arctic islands (see summary in Lim et al., 2005), but are closest to those reported from the lush regions of Mould Bay (0.616 mg/L, Antoniades et al., 2003a) and Banks Island (0.499 mg/L, Lim et al., 2005). The high-elevation oasis sites have a mean TN concentration of 0.206 mg/L, suggesting that these high-elevation sites are more similar to the northern sites ($mean_{northern}$ = 0.330 mg/L) than to those located within the oasis.

Interestingly, the TN:TPu ratios of the two groups of sites do not differ greatly (TN:TPu $mean_{oasis}$ = 98, $mean_{northern}$ = 67) and primary production in both groups is clearly limited by P (Downing and McCauley, 1992). However, when we examine TPu versus TN graphically, we see that there is little relationship between the two variables in either the full data set (graph not shown) or in the northern sites alone (Fig. 2b), but a positive linear relationship between them in the oasis sites (Fig. 2a). This finding suggests that, in the northern sites, different mechanisms control nitrogen and phosphorus delivery to the aquatic ecosystems, but that in the oasis sites the cycles of these nutrients are linked. It is probable that autochthonous production is higher in the oasis sites (e.g., Quesada et al., 1999). This survey is similar to other High Arctic limnological surveys (see below) in that it shows no relationship between either TN or TPu and Chl*a*.

Concentrations of DOC in the oasis sites ($mean_{oasis}$ = 17.3 mg/L) are more than twice the highest previously reported mean values, which were 6.7 mg/L for Mould Bay and 6.1 mg/L for Banks Island. DOC concentrations for the northern sites are similar to averages for most other Arctic limnological surveys ($mean_{northern}$ = 3.4 mg/L). The subset of the high-elevation oasis sites had even lower DOC than the northern sites (mean = 2.3 mg/L). As most DOC is derived from catchment vegetation and aquatic mosses, and as the vegetation is much richer in the oasis than outside, this is not a surprising result. What is especially noteworthy, however, is the unprecedentedly high DOC concentrations from the oasis sites. These high concentrations likely reflect a few ponds that could possibly be considered wetlands because of their very shallow depths and the mosses, grasses, and sedges growing throughout them.

TABLE 2. Summary of selected limnological variables for the oasis sites, with abbreviations as described in Table 1. P values represent the results of t-tests (assuming unequal variance) between the oasis and northern sites. “NS” indicates no significant difference. Full details for other limnological parameters (e.g., metals, rare earth elements) are available in Keatley (2007).

ID	Name	Lat. N	Long. W	Date	Elev (m)	SA (ha)	Pond/ Lake	pH	Cond µS/cm	Chl*a* µg/L	DOC mg/L	DIC mg/L	POC mg/L	PON mg/L	NH_3 mg/L	TKN mg/L
EP1	Skeleton	81°49.798'	71°28.483'	8	296	1.84	L	8.20	175	0.6	5.8	20.7	0.529	0.084	0.014	0.314
EP2		81°49.845'	71°28.352'	8	296	1.00	L	8.17	180	0.6	4.6	22.8	1.240	0.259	0.032	0.296
EP3		81°49.884'	71°28.052'	8	296	0.24	L	8.07	187	0.9	4.1	25.9	1.490	0.334	0.010	0.298
EP4		81°50.721'	71°23.928'	9	300	0.06	P	8.93	235	1.1	31.1	22	1.370	0.131	0.145	2.270
EP5		81°50.752'	71°23.849'	9	297	0.16	P	8.70	443	0.1	29.6	32.4	2.250	0.486	0.063	2.100
EP6		81°50.773'	71°24.815'	9	250	0.06	P	7.90	90	0.5	5.6	7.3	0.900	0.168	0.009	0.289
EP7		81°50.337'	71°20.060'	9	230	1.40	P	8.40	700	1.5	12.5	31.4	0.574	0.086	0.054	0.778
EP8		81°50.474'	71°19.187'	9	220	0.02	P	8.43	650	0.7	40.1	42.7	1.000	0.174	0.034	2.040
EP9		81°50.096'	71°18.539'	9	210	0.34	P	8.40	1650	0.05	35.9	24.5	0.485	0.042	0.063	2.120
EP10		81°48.965'	71°24.995'	10	170	0.05	P	8.50	362	0.6	8.1	20.3	0.449	0.056	0.003	0.318
EP11		81°48.650'	71°26.922'	10	170	0.76	P	8.90	172	1.1	9.1	13.7	0.511	0.057	0.057	0.584
EP12		81°48.590'	71°34.732'	10	190	0.13	P	8.17	1300	0.5	36	55	0.693	0.075	0.011	1.610
EP13		81°48.710'	71°33.614'	10	200	0.02	P	8.37	355	0.05	27.2	42.4	1.550	0.313	0.010	1.150
EP14		81°49.236'	71°32.279'	10	210	0.01	P	8.87	390	0.05	31.8	31.3	0.847	0.082	0.049	1.840
EP15		81°49.899'	71°31.629'	15	300	0.14	P	8.53	560	0.1	9.2	12.2	0.769	0.145	0.044	0.594
EP16		81°49.737'	71°32.251'	15	300	0.50	P	8.73	1000	1	18.2	25	0.854	0.088	0.027	1.380
EP17		81°49.781'	71°30.855'	15	300	0.05	P	8.53	520	0.05	24.1	24.8	0.538	0.049	0.044	1.500
EP18		81°49.306'	71°21.045'	15	160	0.05	P	8.33	470	0.5	13.4	27.4	0.482	0.055	0.047	0.961
EP20		81°49.533'	71°19.999'	15	170	0.09	P	8.03	880	1	21.6	24.5	0.626	0.061	0.007	1.320
EP21		81°49.533'	71°19.999'	15	170	0.07	P	8.33	690	1.1	23.3	26.3	0.387	0.035	0.023	0.992
EP22		81°49.26'	71°45.04'	16	853	1.60	P	8.47	115	0.6	3.9	9.9	0.317	0.052	0.003	0.156
EP23		81°49.298'	71.45.162'	16	860	0.11	P	7.97	91	0.05	2.3	8.9	0.185	0.029	0.018	0.167
EP24		81°49.041'	71°46.886'	16	870	2.80	L	7.53	45	0.5	0.7	4.8	0.425	0.077	0.009	0.087
mean					318	0.50		8.23	490	0.6	17.3	24.2	0.803	0.128	0.034	1.007
median					250	0.13		8.40	390	0.6	13.4	24.5	0.626	0.082	0.027	0.961
max					870	2.80		8.93	1650	1.5	40.1	55	2.250	0.486	0.145	2.270
min					160	0.01		7.53	45	0.05	0.7	4.8	0.185	0.029	0.003	0.087
P value								NS	0.022	NS	NS	0	0	0.001	NS	0

TABLE 2 *Continued*

ID	TdN mg/L	TN mg/L	TPu µg/L	TPf µg/L	SRP µg/L	SiO_2 mg/L	Ca mg/L	K mg/L	Na mg/L	Mg mg/L	Cl mg/L	SO_4 mg/L	Al µg/L	Fe µg/L	TN:TPU	Na:K
EP1	0.354	0.403	9.5	5.2	1.3	4.61	38.80	1.09	1.42	6.53	0.61	41.70	22.7	29.4	42.42	1.30
EP2	0.346	0.561	7.5	3.6	1.0	5.21	41.70	0.85	1.26	5.59	0.58	30.30	1.3	72.3	74.80	1.48
EP3	0.275	0.6345	5.6	3.2	0.8	5.70	44.30	0.98	1.41	6.04	0.56	33.50	20.5	45.4	113.30	1.44
EP4	1.940	2.4035	15.7	9.3	2.3	4.99	35.00	5.70	2.13	17.20	2.27	65.40	8.2	67.7	153.09	0.37
EP5	1.820	2.592	11.7	7.1	2.1	5.91	51.20	8.07	3.29	32.80	3.45	132.00	4.4	149.0	221.54	0.41
EP6	0.316	0.4595	9.2	5.5	1.0	3.16	15.00	0.08	0.73	1.83	0.12	10.10	4.0	143.0	49.95	9.13
EP7	0.746	0.869	11.8	5.2	0.9	0.98	29.60	13.20	68.40	40.70	21.60	260.00	9.3	43.6	73.64	5.18
EP8	1.910	2.2165	24.1	8.5	2.5	7.21	83.20	10.30	5.71	41.10	5.31	211.00	2.0	206.0	91.97	0.55
EP9	1.990	2.167	16.0	9.6	4.2	12.30	344.00	21.80	29.60	97.70	16.70	1150.00	13.8	359.0	135.44	1.36
EP10	0.328	0.3765	9.5	5.6	1.0	2.11	60.30	3.39	1.95	14.90	1.04	131.00	42.1	86.5	39.63	0.58
EP11	0.567	0.6435	13.5	6.4	0.7	2.49	29.70	2.17	1.09	4.12	0.84	32.90	19.6	231.0	47.67	0.50
EP12	1.470	1.6875	13.0	10.5	4.5	12.20	234.00	32.00	28.70	87.10	15.20	751.00	2.2	430.0	129.81	0.90
EP13	1.380	1.4655	9.7	5.8	3.7	6.51	59.80	5.37	3.81	17.20	3.54	51.60	9.6	178.0	151.08	0.71
EP14	1.610	1.9245	20.6	7.1	2.2	5.33	67.20	4.83	4.47	22.40	2.92	130.00	4.2	183.0	93.42	0.93
EP15	0.645	0.7415	10.4	4.6	0.3	1.14	41.00	2.86	3.22	18.90	1.19	127.00	6.9	68.2	71.30	1.13
EP16	1.210	1.514	12.0	6.9	1.5	2.66	107.00	19.90	13.70	117.00	5.34	680.00	4.7	92.4	126.17	0.69
EP17	1.430	1.558	7.6	6.1	1.9	13.90	90.50	3.94	5.74	34.20	1.56	262.00	12.7	73.5	205.00	1.46
EP18	0.927	1.036	17.1	7.0	0.8	2.30	64.90	6.32	1.92	34.50	1.42	189.00	5.9	117.0	60.58	0.30
EP20	0.030	1.3835	9.4	6.1	0.8	8.19	191.00	8.32	4.79	38.10	4.76	494.00	8.5	610.0	147.18	0.58
EP21	0.907	1.0295	7.8	6.4	0.9	11.60	148.00	7.49	2.77	25.40	1.89	329.00	3.0	274.0	131.99	0.37
EP22	0.179	0.2105	8.5	2.4	0.3	1.62	22.40	0.64	1.21	1.94	0.64	18.90	23.7	41.5	24.76	1.89
EP23	0.207	0.227	4.9	2.4	0.1	1.42	18.30	0.55	1.06	1.76	0.37	16.60	31.4	52.1	46.33	1.93
EP24	0.109	0.182	4.8	2.0	0.1	1.56	8.87	0.25	0.52	0.83	0.36	3.25	37.1	53.4	37.92	2.08
mean	0.900	1.14	11.3	5.9	1.5	5.35	79.38	6.96	8.21	29.04	4.01	223.92	12.9	156.8	98.65	1.53
median	0.746	1.03	9.7	6.1	1.0	4.99	51.20	4.83	2.77	18.90	1.56	130.00	8.5	92.4	91.97	0.93
max	1.990	2.59	24.1	10.5	4.5	13.90	344.00	32.00	68.40	117.00	21.60	1150.00	42.1	610.0	221.54	9.13
min	0.030	0.18	4.8	2.0	0.1	0.98	8.87	0.08	0.52	0.83	0.12	3.25	1.3	29.4	24.76	0.30
P value	0	0	0.007	0	0.018	0	NS	0.005	NS	NS	NS	NS	NS	NS	0.041	0.007

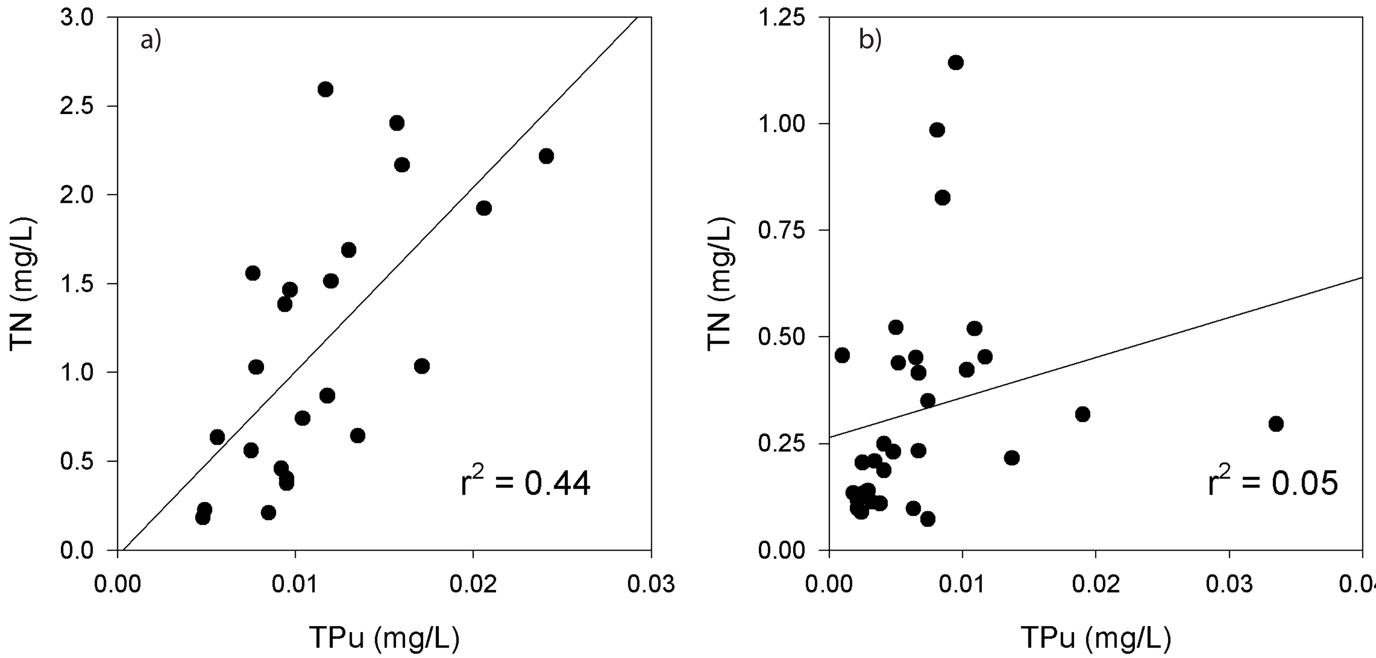

FIG. 2. Plots of total phosphorus unfiltered (TPu) versus total nitrogen (TN) in a) the oasis sites, and b) the northern sites. While there is little relationship between TPu and TN in the northern region, there is a clear positive relationship with TPu and TN in the oasis sites, suggesting that different factors control nutrient cycling within the two regions.

Previously reported mean SiO_2 concentrations for High Arctic lakes and ponds have ranged from 0.41 mg/L (Melville Island, Keatley et al., 2007; and Mould Bay, Antoniades et al., 2003a) to 1.69 mg/L (Axel Heiberg Island, Michelutti et al. 2002b). In our study, the oasis sites had average SiO_2 concentrations of 5.35 mg/L, while the northern sites had an average of 1.47 mg/L. While both our zones have high SiO_2 concentrations, likely reflective of the bedrock geology, the oasis sites greatly exceed previously reported Canadian High Arctic SiO_2 concentrations. These high concentrations may be attributable to the increased action of weathering due to enhanced runoff during late spring snowmelt under these warmer oasis conditions. In addition, because our SiO_2 measurements were taken from unfiltered water samples, the high SiO_2 values may also reflect increased abundance of siliceous algae within the water samples of the more productive oasis sites.

It is hypothesized that warmer conditions will result in higher concentrations of nutrients and related variables (e.g., Douglas and Smol, 1999), and consequently, higher biological production. While terrestrial production was indeed high in the oasis sites, there was no significant difference between the two zones with respect to Chl*a*, our proxy for autochthonous phytoplanktonic production ($mean_{oasis} = 0.6$ mg/L, $mean_{northern} = 0.5$ mg/L). Likewise, there was no relationship between Chl*a* and either TN or TPu, regardless of whether we examined the two zones together or separately, or whether we examined the oasis sites with or without the high-elevation sites. Chl*a* concentrations have similarly borne little resemblance to other typical indicators of high production (such as high P and N concentrations) in other Canadian High Arctic limnological surveys (Michelutti et al., 2002a, b; Antoniades et al., 2003a, b; Lim et al., 2005). This has been attributed to discrepancies between measuring Chl*a* in the water column, whereas most of the primary production occurs in the periphytic habitat (Vezina and Vincent, 1997; Villeneuve et al., 2001; Bonilla et al., 2005). It is reasonable to suggest that a similar phenomenon may occur here.

Statistical Results

The PCA ordination biplot of all sites (Fig. 3) indicates two main directions of variation in the measured environmental data: Axis 1 includes nutrients and related variables (TPu, TPf, DOC, TdN, SiO_2) as well as conductivity and major ions, and explains 52.9% of the variation in the sites. Meanwhile, Axis 2 represents a trace metal gradient and explains 16% of the variation (Fig. 3). For the sake of clarity in the ordination plot (Fig. 3), we have chosen to remove some highly correlated variables based on the Pearson correlation matrix (Table 3). For example, SiO_2 has replaced the highly correlated variables of POC and PON, TdN represents both TKN and TdN, and the metals U, V, Zn, Co, Cr, Be, Mg, and Mn have been removed. The following ecologically important variables could not be normalized and thus were plotted passively in the ordination (Chl*a*, DIC, K, SO_4, Cl), along with the geographical variables (elevation, latitude, longitude, temperature).

As expected, the oasis sites plot closer to each other than to the northern sites (Fig. 3), and most of these lie along the higher end of Axis 1. This once again indicates that conductivity and nutrients and related variables seem to distinguish the oasis sites even in the presence of all other measured limnological variables. Some exceptions

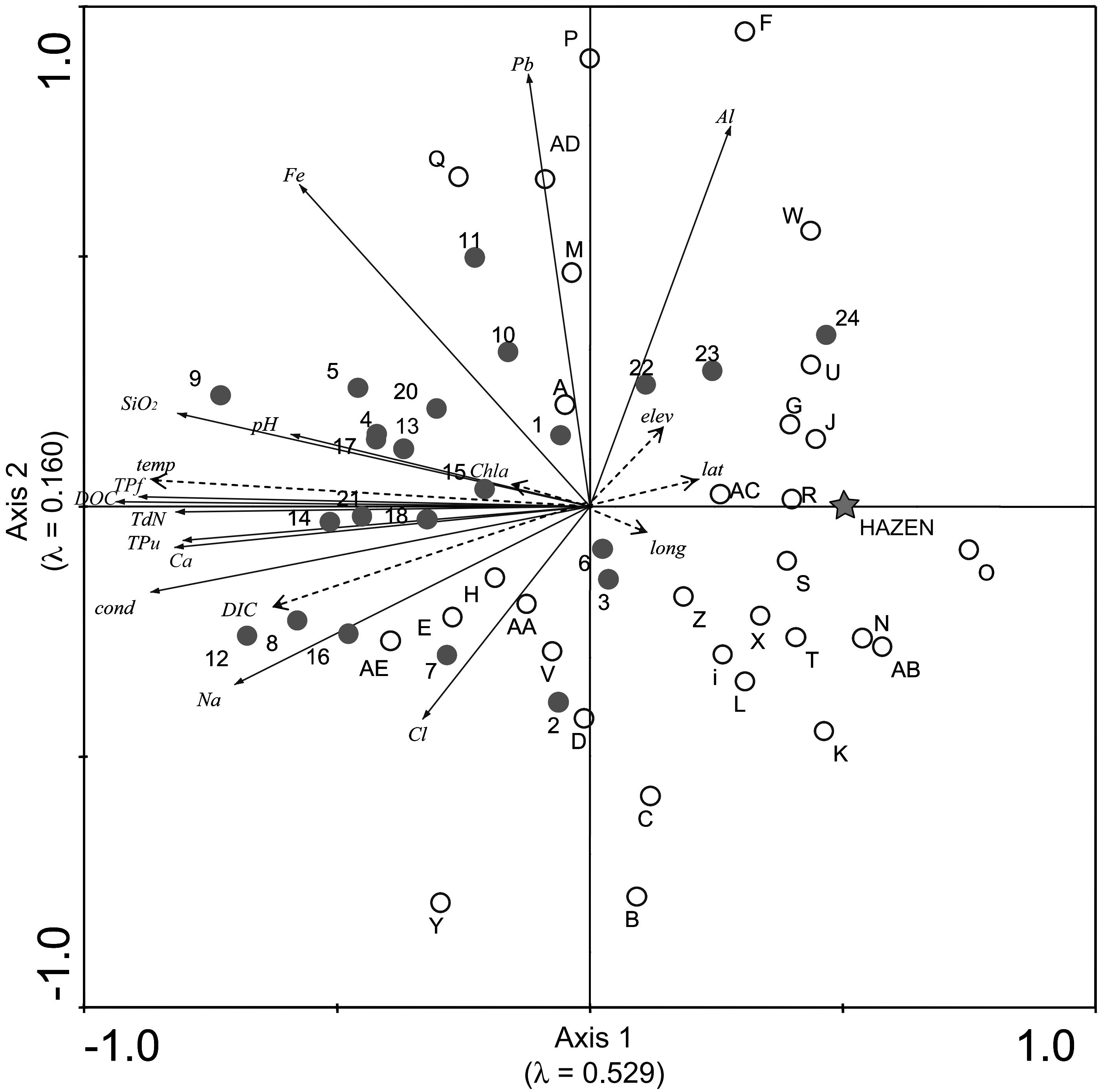

FIG. 3. Biplot of a principal components analysis (PCA) of measured limnological variables for all sites. Oasis sites are represented by filled circles and northern sites are represented by open circles. Lake Hazen is kept separate because of its extremely large size and is represented by a star. Axis 1 most closely represents nutrients and related variables, pH, and conductivity, and explains 52.9% of the variance in the data set. Axis 2 most closely represents a gradient of metals and explains 16% of the variance in the data set. The dashed lines represent variables that were run passively in the ordination.

to this general trend include high-elevation oasis sites (EP22, 23, and 24) that were more dilute and less nutrient-rich than most other oasis sites (see above). These high-elevation sites also had persistent ice cover and very little vegetation in their catchments. The northern sites that plotted closest to our oasis sites on the PCA (AE, E, H) tended to be small ponds with relatively rich vegetation when compared to the rest of the northern sites. The two sites that plotted at the positive end of Axis 1 were the least nutrient-rich and most dilute in the entire data set. These sites were Lake Hazen, a very large lake, and EPO, a pond located on top of a high mountain glacier with no vegetation, soil, or even rock in its watershed.

In an attempt to quantitatively determine the main environmental gradients defining the oasis and northern zones, a Canonical Variates Analysis (CVA) was

TABLE 3. Pearson correlation matrix with Bonferroni-adjusted probabilities. Significantly correlated variables are shown in bold ($p < 0.01$) or italics ($p < 0.05$).

	pH	COND	SiO_2	Ca	POC	PON	DOC	TdN	TPu	TPf	Mg	Na	TKN	Al	Fe	Chl*a*	DIC	Cl	SO_4	K	SRP
pH	1																				
COND	0.467	1																			
SiO_2	0.347	**0.67**	1																		
Ca	0.366	**0.92**	**0.772**	1																	
POC	0.454	**0.519**	**0.729**	*0.525*	1																
PON	0.292	0.391	0.631	0.371	**0.92**	1															
DOC	*0.516*	0.734	**0.749**	**0.659**	**0.698**	**0.593**	1														
TdN	**0.593**	**0.599**	**0.606**	*0.512*	**0.597**	**0.554**	**0.8**	1													
TPu	0.416	0.613	**0.557**	**0.569**	**0.566**	*0.523*	**0.742**	**0.595**	1												
TPf	0.494	0.665	**0.688**	**0.612**	**0.649**	**0.55**	**0.879**	**0.775**	**0.751**	1											
Mg	**0.557**	**0.943**	**0.586**	**0.811**	0.48	0.354	**0.694**	**0.616**	*0.495*	**0.61**	1										
Na	0.349	0.75	0.39	**0.586**	0.336	0.292	**0.616**	*0.5*	**0.595**	**0.55**	**0.723**	1									
TKN	**0.563**	**0.74**	**0.734**	**0.66**	**0.708**	**0.616**	**0.943**	**0.842**	**0.753**	**0.9**	**0.718**	**0.624**	1								
Al	-0.06	-0.243	-0.089	-0.184	-0.18	-0.201	-0.324	-0.29	-0.315	-0.284	-0.23	-0.259	-0.354	1							
Fe	0.228	0.372	**0.626**	0.414	*0.518*	0.44	**0.593**	0.395	0.398	*0.514*	0.316	0.164	*0.533*	0.268	1						
Chl*a*	0.044	0.036	0.116	-0.008	0.147	0.111	0.237	0.096	0.203	0.262	-0.036	0.047	0.242	-0.023	0.19	1					
DIC	0.511	**0.658**	0.525	0.541	0.448	0.357	**0.576**	**0.545**	0.337	0.44	**0.772**	**0.547**	**0.581**	-0.295	0.233	-0.137	1				
Cl	0.175	*0.497*	-0.001	0.327	0.035	0.002	0.187	0.18	0.331	0.259	0.469	**0.76**	0.253	-0.183	-0.139	0.075	0.272	1			
SO_4	0.077	**0.764**	0.475	**0.784**	0.251	0.125	0.454	0.331	0.477	0.486	**0.626**	**0.591**	0.468	-0.209	0.208	0.103	0.223	**0.568**	1		
K	0.232	**0.728**	0.469	**0.608**	0.351	0.262	**0.667**	**0.567**	0.445	**0.603**	**0.719**	**0.695**	**0.638**	-0.275	0.405	0.147	**0.555**	0.477	**0.702**	1	
SRP	0.241	0.607	**0.594**	**0.646**	*0.527*	0.426	**0.65**	**0.59**	**0.558**	**0.601**	*0.535*	0.481	**0.599**	-0.251	0.367	-0.017	0.417	0.342	**0.685**	**0.663**	1

performed to identify environmental variables that could significantly discriminate between clusters of samples. Using this method, only DOC explained a significant portion of the variation between the oasis and northern sites ($p = 0.001$). However, DOC was also highly correlated to many nutrients and related variables (including TPu, TPf, TdN, TKN, POC, and PON, Table 3, Fig. 3), and thus, while DOC was the only significant variable retained in the analysis, it represents a number of correlated water chemistry variables.

Historical Data

Some of the sites we sampled at Lake Hazen had been part of a Defence Research Board limnological study in 1963 (Oliver and Corbet, 1966). These historical data represent the earliest available quantitative limnological data for the Canadian High Arctic. Instrumental temperature records from Alert and Eureka, as well as proxy climate indicators from Alexandra Fiord (Rayback and Henry, 2006) and glacier mass balance records from around north central Ellesmere Island (Braun et al., 2004), indicate a relatively cool period in the 1960s compared to the late 1990s and the early 21st century. Temperature records from the DRB study indicate average July 1963 temperatures of 6.6˚C (Oliver and Corbet, 1966), compared to an average temperature of 12.8˚C during our field season in July 2003. Since limnological characteristics such as pH and specific conductivity also change over the course of a growing season in High Arctic lakes and ponds (Douglas and Smol, 1994), comparisons between the two data sets must be made with caution. Nevertheless, there are no other Arctic regions with available water chemistry data from the 1960s, and so a comparison, even at a basic level, is warranted.

Interestingly, in almost all sites, we see a slight increase in pH (Fig. 4a) in 2003 relative to 1963. By examining the identical sites 40 years apart, we have removed any influence of differences in geology. Recall that in our modern survey, we did not record significant differences between our pH values in the oasis and northern sites, and that this was likely because of the overriding influence of geology. By removing the influence of geology (i.e., resampling the same sites), we may be more directly tracking limnological differences related to a longer growing season that would be reflected in the warmer temperatures.

Specific conductivity showed no clear pattern between 2003 and 1963, but instead appears to be related to sampling date (Fig. 4b). Not surprisingly, specific conductivity is in general much higher later in the growing season (Fig. 4b), although this pattern is not without exception (see EP17, for example). Indeed, seasonal studies both at the Hazen Camp in 1963 (Oliver and Corbet, 1966) and elsewhere in the High Arctic (Douglas and Smol, 1994) have noted that specific conductivity increased in the majority of sites over the course of the summer season because of evaporation. During the 1963 study at Hazen Camp, the specific conductivity fluctuated on the order of ~500 μS/cm over the course of the ice-free season, with some ponds drying up completely (Oliver and Corbet, 1966). In our modern comparison, we conducted our field sampling within a short time window of less than two weeks, and thus we largely removed the seasonal effect of changes in conductivity. Changes in the precipitation regime would also influence conductivity. Although there has been a significant increase in total annual precipitation at Eureka, there has been no clear trend in annual precipitation at Alert, the closest meteorological station, over the last 50 years (Environment Canada, 2007). Concentrations of K and SiO_2 are both higher in most sites in 2003

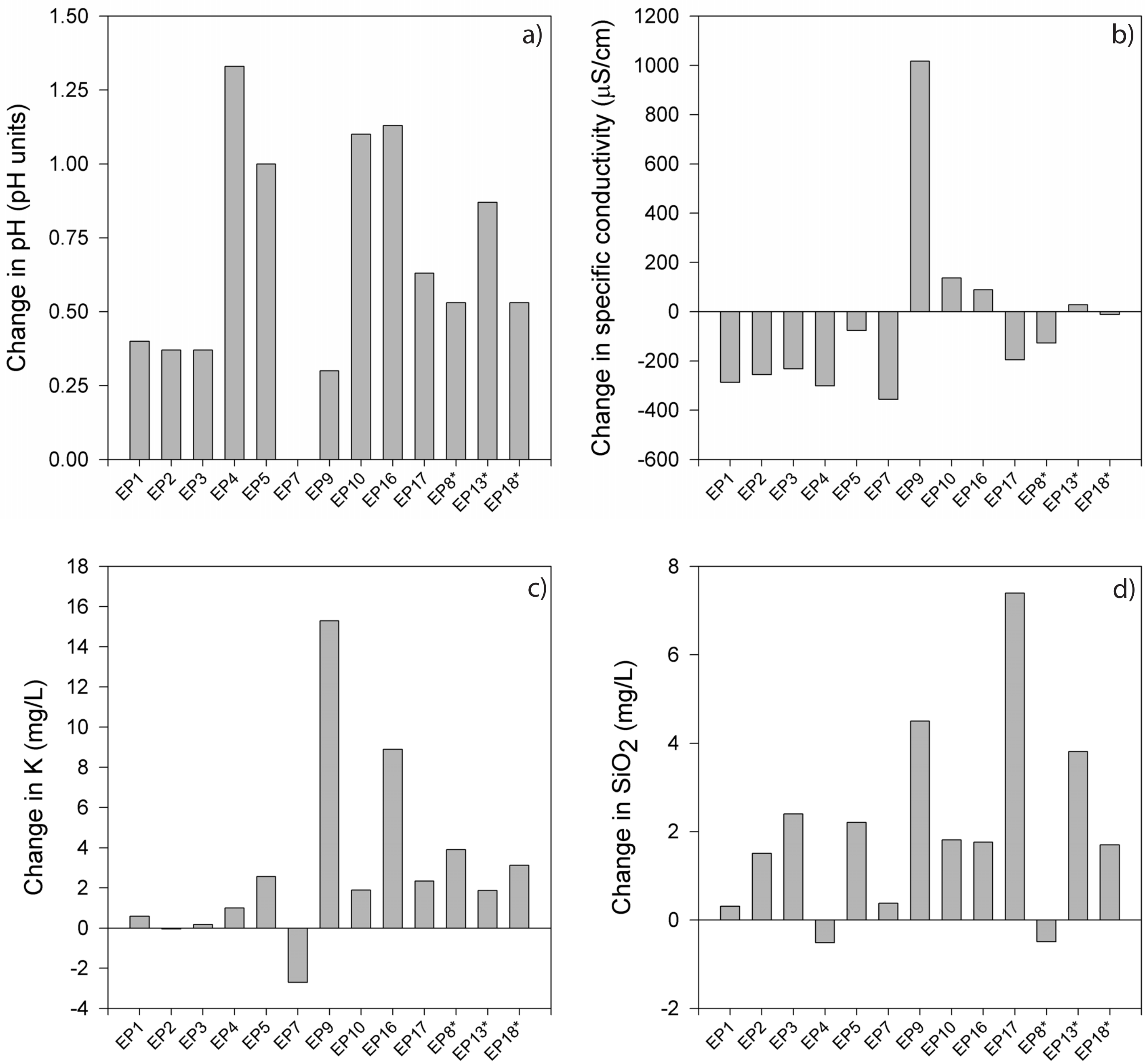

FIG. 4. Histograms indicating the change in the values of selected limnological variables in 2003 relative to 1963 for a) pH, b) specific conductivity, c) K, and d) SiO_2. Site names with * indicate sites for which identification was approximate.

compared to 1963 (Fig. 4c, d), but Ca, Mg, Na, Cl, and SO_4 all show complex patterns that are similar to those found for conductivity (data not shown).

SUMMARY AND CONCLUSIONS

We provide a limnological survey of aquatic habitats located throughout the diverse landscape of northern Ellesmere Island and compare these to other High Arctic limnological surveys. The concentrations of nutrients and DOC reported from the oasis ponds and lakes are among the highest, and in some cases the highest yet reported from the Canadian High Arctic. The oasis sites at Hazen Camp are more similar to oasis sites located at Mould Bay, Prince Patrick Island, Banks Island, and Bathurst Island (many hundreds of kilometres to the southwest) than to those located within a few hundred kilometres on Ellesmere Island. Meanwhile, the northern Ellesmere lakes and ponds from our data set are more similar to those located within the polar deserts of Alert, Axel Heiberg Island, and Devon Island.

We compared point samples of limnological characteristics between aquatic habitats located within an Arctic oasis at Hazen Camp to those located outside this oasis area to determine if these smaller, warmer water bodies had higher specific conductivity and increased nutrient concentrations. Our comparisons indicate that smaller sites located in warmer and more lushly vegetated Arctic regions have distinctive water chemistry, particularly with respect to nutrients and related variables. In our data set, these higher concentrations of nutrients and related variables (particularly DOC and correlated variables) were significant despite differences in latitude, elevation, and surface area between the oasis and northern sites. Interestingly, the three high-elevation oasis ponds were more similar to the polar desert sites than to the other Arctic oasis ponds with respect to specific conductivity and nutrients and related variables.

A comparison of water chemistry from a subset of the oasis sites that were first examined in 1963 to data we collected in 2003 showed that some sites had higher pH in 2003 than they did in 1963, consistent with documented warming temperatures. Comparisons of specific conductivity, however, appear to be more related to sampling date.

In summary, aquatic ecosystems in this Arctic oasis have distinct water chemistry from those located in the nearby polar desert. We associate this difference with increased catchment vegetation, greater runoff from the watershed, and enhanced evaporation, all of which can be linked to the warmer temperatures of the oasis. Our results may represent a preview of how other Arctic freshwater systems might change under a continued Arctic warming scenario.

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REFERENCES

AIKEN, S.G., DALLWITZ, M.G., CONSAUL, L.L., McJANNET, C.L., BOLES, R.L., ARGUS, G.W., GILLETT, J.M., SCOTT, P.J., ELVEN, R., LEBLANC, M.C., GILLESPIE, L.J., BRYSTING, A.K., SOLSTAD, H., and HARRIS, J.G. 1999 onwards. Flora of the Canadian Arctic Archipelago: Descriptions, illustrations, identification, and information retrieval. Version: 1 October 2005. http://www.mun.ca/biology/delta/arcticf/.

ANTONIADES, D., DOUGLAS, M.S.V., and SMOL, J.P. 2003a. Comparative limnology of two Canadian High Arctic regions: Alert (Ellesmere Island, NU) and Mould Bay (Prince Patrick Island, NWT). Archiv für Hydrobiologie 158:485–516.

———. 2003b. Physical and chemical limnology of 24 ponds and one lake from Isachsen, Ellef Ringnes Island, Canadian High Arctic. International Review of Hydrobiology 88:519–538.

———. 2005. Quantitative estimates of environmental changes in the Canadian High Arctic inferred from diatoms in lake and pond sediments. Journal of Paleolimnology 33:349–360.

BEDNARSKI, J. 1994. Geomorphology. In: Resource description and analysis: Ellesmere Island, National Park Reserve, Chapter 3. Winnipeg, Manitoba: National Resource Conservation Section, Prairie and Northern Region, Parks Canada, Department of Canadian Heritage. 1–119.

BLISS, L.C. 1977a. Introduction. In: Truelove Lowland, Devon Island, Canada: A High Arctic ecosystem. Edmonton: University of Alberta Press. 1–12.

———, ed. 1977b. Truelove Lowland, Devon Island, Canada: A High Arctic ecosystem. Edmonton: University of Alberta Press. 714 p.

BONILLA, S., VILLENEUVE, V., and VINCENT, W.F. 2005. Benthic and planktonic algal communities in a High Arctic lake: Pigment structure and contrasting responses to nutrient enrichment. Journal of Phycology 41:1120–1130.

BRAUN, C., HARDY, D.R., and BRADLEY, R.S. 2004. Mass balance and area changes of four High Arctic plateau ice caps, 1959–2002. Geografiska Annaler Series A-Physical Geography 86A:43–52.

CHRISTIE, R.L. 1957. Geological reconnaissance of the north coast of Ellesmere Island, District of Franklin, Northwest Territories. Paper 56-9. Ottawa: Department of Mines and Technical Surveys. 40 p.

———. 1964. Geological reconnaissance of northeastern Ellesmere Island, District of Franklin. Memoir 331. Ottawa: Geological Survey of Canada. 79 p.

CROASDALE, H. 1973. Freshwater algae of Ellesmere Island, N.W.T. Ottawa: National Museums of Canada. 131 p.

DOUGLAS, M.S.V., and SMOL, J.P. 1994. Limnology of High Arctic ponds (Cape Herschel, Ellesmere Island, N.W.T.). Archiv für Hydrobiologie 131:410–434.

———. 1999. Freshwater diatoms as indicators of environmental change in the High Arctic. In: Stoermer, E.F., and Smol, J.P., eds. The diatoms: Applications for the environmental and earth sciences. Cambridge: Cambridge University Press. 227–244.

DOWNING, J.A., and McCAULEY, E. 1992. The nitrogen-phosphorus relationship in lakes. Limnology and Oceanography 37:936–945.

EDLUND, S.A., and ALT, B.T. 1989. Regional congruence of vegetation and summer climate patterns in the Queen Elizabeth Islands, Northwest Territories, Canada. Arctic 42:3–23.

ENVIRONMENT CANADA. 1994. Manual of analytical methods, 2 Vols. Burlington, Ontario: National Laboratory for Environmental Testing, Canadian Centre for Inland Waters.

———. 2004. Canadian climate normals 1971–2000. Environment Canada. http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html.

———. 2007. Climate data online. http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html.

FRANCE, R.L. 1993. The Lake Hazen trough: A late winter oasis in a polar desert. Biological Conservation 63:149–151.

FREEDMAN, B., SVOBODA, J., and HENRY, G.H.R. 1994. Alexandra Fiord: An ecological oasis in the polar desert. In: Svoboda, J., and Freedman, B., eds. Ecology of a polar oasis: Alexandra Fiord, Ellesmere Island, Canada. Toronto: Captus University Publications. 1–12.

GIBSON, J.A.E., VINCENT, W.F., VAN HOVE, P., BELZILE, C., WANG, X., and MUIR, D. 2002. Geochemistry of ice-covered, meromictic Lake A in the Canadian High Arctic. Aquatic Geochemistry 8:97–119.

GRAY, D.R. 1994. Ecology. In: Resource description and analysis: Ellesmere Island, National Park Reserve, Chapter 1. Winnipeg, Manitoba: National Resource Conservation Section, Prairie and Northern Region, Parks Canada, Department of Canadian Heritage. 1–72.

HAMILTON, P.B., LEAN, D.R.S., and POULIN, M. 1994. The physicochemical characteristics of lakes and ponds from the northern regions of Ellesmere Island. In: Hamilton, P.B., ed. Proceedings of the Fourth Arctic-Antarctic Diatom Workshop, Canadian Museum of Nature. Canadian Technical Report of Fisheries and Aquatic Sciences 1957:57–63.

HAMILTON, P.B., GAJEWSKI, K., ATKINSON, D.E., and LEAN, D.R.S. 2001. Physical and chemical limnology of 204 lakes from the Canadian Arctic Archipelago. Hydrobiologia 457:133–148.

HENRY, G.H.R., SVOBODA, J., and FREEDMAN, B. 1990. Standing crop and net production of sedge meadows of an ungrazed polar desert oasis. Canadian Journal of Botany 68: 2660–2667.

JUGGINS, S., and TER BRAAK, C.J.F. 1992. CALIBRATE — a program for species-environment calibration by [weighted averaging] partial least squares regression. London: Environmental Change Research Centre, University College.

KEATLEY, B.E. 2007. Diatoms as indicators of environmental change under three distinct ecosystem types in the Canadian High Arctic. PhD Thesis. Department of Biology, Queen's University, Kingston, Ontario.

KEATLEY, B.E., DOUGLAS, M.S.V., and SMOL, J.P. 2007. Physical and chemical limnological characteristics across environmental gradients on Melville Island, Nunavut/N.W.T., High Arctic Canada. Fundamental and Applied Limnology 168:355–376.

LAURION, I., VINCENT, W.F., and LEAN, D.R.S., 1997. Underwater ultraviolet radiation: Development of spectral models for northern high latitude lakes. Photochemistry and Photobiology 65:107–114.

LEPŠ, J., and ŠMILAUER, P. 2003. Multivariate analysis of ecological data using CANOCO. London: Cambridge University Press. 282 p.

LIM, D.S.S., and DOUGLAS, M.S.V. 2003. Limnological characteristics of 22 lakes and ponds in the Haughton Crater region of Devon Island, Nunavut, Canadian High Arctic. Arctic, Antarctic, and Alpine Research 35:509–519.

LIM, D.S.S., DOUGLAS, M.S.V., SMOL, J.P., and LEAN, D.R.S. 2001. Physical and chemical limnological characteristics of 38 lakes and ponds on Bathurst Island, Nunavut, Canadian High Arctic. International Review of Hydrobiology 86:1–22.

LIM, D.S.S., DOUGLAS, M.S.V., and SMOL, J.P. 2005. Limnology of 46 lakes and ponds on Banks Island, NWT, Canadian Arctic Archipelago. Hydrobiologia 545:11–32.

McLAREN, I.A. 1964. Zooplankton of Lake Hazen Ellesmere Island and a nearby pond with special reference to copepod *Cyclops scutifer* Sars. Canadian Journal of Zoology 42: 613–629.

McNEELY, R.N., NEIMANIS, V.P., and DWYER, L. 1979. Water quality sourcebook: A guide to water quality parameters. Ottawa: Minister of Supply and Services Canada. 88 p.

MICHELUTTI, N., DOUGLAS, M.S.V., LEAN, D.R.S., and SMOL, J.P. 2002a. Physical and chemical limnology of 34 ultra-oligotrophic lakes and ponds near Wynniatt Bay, Victoria Island, Arctic Canada. Hydrobiologia 482:1–13.

MICHELUTTI, N., DOUGLAS, M.S.V., MUIR, D.C.G., WANG, X., and SMOL, J.P. 2002b. Limnological characteristics of 38 lakes and ponds on Axel Heiberg Island, High Arctic Canada. International Review of Hydrobiology 87:385–399.

MINNS, C.K. 1977. Limnology of some lakes on Truelove Lowland. In: Bliss, L.C., ed. Truelove Lowland, Devon Island, Canada: A High Arctic ecosystem. Edmonton: University of Alberta Press. 567–586.

MUC, M., and BLISS, L.C. 1977. Plant communities of Truelove Lowland. In: Bliss, L.C., ed. Truelove Lowland, Devon Island, Canada: A High Arctic ecosystem. Edmonton: University of Alberta Press. 143–154.

OLIVER, D.R., and CORBET, P.S. 1966. Aquatic habitats in a High Arctic locality: The Hazen Camp study area, Ellesmere Island, N.W.T. Ottawa: Department of National Defence. 115 p.

PRENTKI, R.T., MILLER, M.C., BARSDATE, R.J., ALEXANDER, V., KELLY, J., and COYNE, P. 1980. Chemistry. In: Hobbie, J.E., ed. Limnology of tundra ponds, Barrow Alaska. Stroudsburg: Dowden, Hutchinson and Ross, Inc. 76–178.

QUESADA, A., VINCENT, W.F., and LEAN, D.R.S. 1999. Community and pigment structure of Arctic cyanobacterial assemblages: The occurrence and distribution of UV-absorbing compounds. FEMS Microbiology Ecology 28:315–323.

RAYBACK, S.A., and HENRY, G.H.R. 2006. Reconstruction of summer temperature for a Canadian High Arctic site from retrospective analysis of the dwarf shrub, *Cassiope tetragona*. Arctic, Antarctic, and Alpine Research 38:228–238.

SMITH, I.R. 2002. Diatom-based Holocene paleoenvironmental records from continental sites on northeastern Ellesmere Island, High Arctic, Canada. Journal of Paleolimnology 27:9–28.

SMOL, J.P., WOLFE, A.P., BIRKS, H.J.B., DOUGLAS, M.S.V., JONES, V.J., KORHOLA, A., PIENITZ, R., RÜHLAND, K., SORVARI, S., ANTONIADES, D., BROOKS, S.J., FALLU, M.-A., HUGHES, M., KEATLEY, B.E., LAING, T.E., MICHELUTTI, N., NAZAROVA, L., NYMAN, M., PATERSON, A.M., PERREN, B., QUINLAN, R., RAUTIO, M., SAULNIER-TALBOT, E., SIITONENI, S., SOLOVIEVA, N., and WECKSTRÖM, J. 2005. Climate-driven regime shifts in the biological communities of Arctic lakes. Proceedings of the National Academy of Sciences of the United States of America 102:4397–4402.

SOPER, J.H., and POWELL, J.M. 1985. Botanical studies in the Lake Hazen Region, northern Ellesmere Island, Northwest Territories, Canada. Ottawa: National Museums of Canada. 67 p.

TER BRAAK, C.J.F., and ŠMILAUER, P. 2002. CANOCO reference manual and CANOdraw for Windows user guide: Software for Canonical Community Ordination (Version 4.5). Ithaca, New York: Microcomputer Power.

THOMPSON, W. 1994. Climate. In: Resource description and analysis: Ellesmere Island, National Park Reserve, Chapter 5. Winnipeg, Manitoba: National Resource Conservation Section, Prairie and Northern Region, Parks Canada, Department of Canadian Heritage. 1–78.

VAN HOVE, P., BELZILE, C., GIBSON, J.A.E., and VINCENT, W.F. 2006. Coupled landscape-lake evolution in High Arctic Canada. Canadian Journal of Earth Sciences 43:533–546.

VEZINA, S., and VINCENT, W.F. 1997. Arctic cyanobacteria and limnological properties of their environment: Bylot Island, Northwest Territories, Canada (73 degrees N, 80 degrees W). Polar Biology 17:523–534.

VILLENEUVE, V., VINCENT, W.F., and KOMÁREK, J. 2001. Community structure and microhabitat characteristics of cyanobacterial mats in an extreme High Arctic environment: Ward Hunt Lake. Nova Hedwigia 123:199–224.

WETZEL, R.G. 1983. Limnology, 2nd ed. Philadelphia: Saunders Publishing. 767 p.