

Evidence of eutrophication in Arctic lakes¹

Paola Ayala-Borda, Connie Lovejoy, Michael Power, and Milla Rautio

Abstract: Lakes and ponds are dominant components of Arctic landscapes and provide food and water for northern communities. In the Greiner Lake watershed, in Cambridge Bay (Nunavut, Canada), water bodies are small (84% <5 ha) and shallow (99% <4 m deep). Such characteristics make them vulnerable to eutrophication as temperatures rise and nutrient concentrations from the greening landscape increase. Here, we investigated and compared 35 lakes and ponds in the Greiner watershed in August 2018 and 2019 to determine their current trophic states based on their chemical composition and phytoplankton communities. The ponds had higher trophic status than the lakes, but overall, most sites were oligotrophic. Lake ERA5, located upstream of any direct human influence was classified as eutrophic due to high total phosphorus (32.3 $\mu\text{g}\cdot\text{L}^{-1}$) and a high proportion of Cyanobacteria (42.9% of total phytoplankton biovolume). Satellite imagery suggests the lake may have been eutrophic for the last 30 years. We hypothesize that the coupled effects of catchment characteristics and elevated local snow accumulation patterns promote higher nutrient leaching rates from the soils. We recommend further analysis and monitoring as eutrophication could become more widespread with ongoing climate change and the associated increases in temperature, precipitation, and catchment–lake coupling.

Key words: eutrophication, Arctic lakes, climate change, nutrients, cyanobacteria.

Résumé : Les lacs et les étangs sont des composantes dominantes des paysages Arctiques et ils fournissent de la nourriture et de l'eau aux communautés nordiques. Dans le bassin versant du lac Greiner, à Cambridge Bay (Nunavut, Canada), les plans d'eau sont petits (84 % <5 ha) et peu profonds (99 % <4 m de profondeur). De telles caractéristiques les rendent vulnérables à l'eutrophisation avec la hausse des températures et l'augmentation des concentrations de nutriments provenant du verdissement du paysage. Ici, les auteurs ont étudié et comparé 35 lacs et étangs du bassin versant du lac Greiner en août 2018 et 2019 afin de déterminer leurs états trophiques actuels en fonction de leur composition chimique et de leurs communautés phytoplanctoniques. Les étangs avaient un état trophique plus élevé que les lacs, mais dans l'ensemble, la plupart des sites étaient oligotrophes. Le lac ERA5, situé en amont de toute influence humaine directe, a été classé comme eutrophe en raison d'un taux élevé de phosphore total (32,3 $\mu\text{g}\cdot\text{L}^{-1}$) et d'une forte proportion de cyanobactéries (42,9 % du biovolume total de phytoplancton). L'imagerie satellitaire suggère que le lac a pu être eutrophique au cours des 30 dernières années. Les auteurs

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émettent l'hypothèse que les effets couplés des caractéristiques du bassin versant et des patrons d'accumulation de neige locale élevée favorisent des taux de lixiviation de nutriments plus élevés à partir des sols. Ils recommandent une analyse et une surveillance plus poussées, car l'eutrophisation pourrait devenir plus répandue avec les changements climatiques en cours et les augmentations associées de la température, des précipitations et du couplage bassin versant–lac. [Traduit par la Rédaction]

Mots-clés : eutrophisation, lacs Arctiques, changements climatiques, nutriments, cyanobactéries.

Introduction

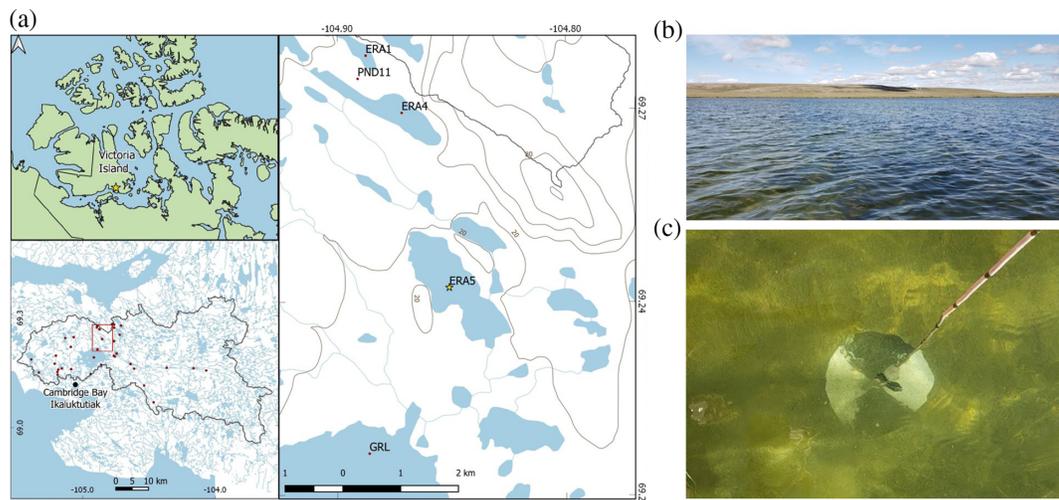
Lakes and ponds are a striking component of many Arctic landscapes and provide migratory nesting birds, resident animals, and humans with food and fresh water. The water bodies experience strong seasonal fluctuations, from complete ice cover, with low or no light and hypoxic conditions during much of the year, to open water, water column mixing, full oxygenation, air temperatures above freezing and 24 h light cycles during the brief summer. Their limnological characteristics and those of the surrounding landscapes make them sensitive to small changes in the environment and within the context of Arctic freshwater science they are typically viewed as “sentinels of climate change” (Vincent et al. 2009).

Arctic lakes are impacted by climate change that is affecting the Arctic twice as fast as other areas in the world. Increasing temperatures have had measurable effects on many different levels of Arctic ecosystems, from earlier ice breakup (Vincent et al. 2011; Šmejkalová et al. 2016; Cooley et al. 2020) through increases in vegetation cover (Campbell et al. 2020) to changes in bird populations (Menu et al. 2002). With temperature-driven permafrost thaw, changes in hydrologic connectivity leading to erosion are also becoming more evident (Liljedahl et al. 2016), along with increasing evaporation/precipitation ratios leading to higher ion concentrations or even desiccation of shallow water bodies (Smol and Douglas 2007). The resulting mineral mobilization increases phosphorus (P) input to freshwaters, especially in regions with naturally high P concentrations in the bedrock and soil (Vonk et al. 2015). All these changes have an effect on freshwater communities, altering plankton diversity and production (Wrona et al. 2016). An additional potential consequence of warming is the increasing prevalence of phytoplankton groups, such as Cyanobacteria, that prefer warmer temperatures and that have already been reported to respond to climate change in subarctic ponds (Przytulska et al. 2017).

Arctic lakes are typically oligotrophic, or even ultraoligotrophic, (Hamilton et al. 2001; Michelutti et al. 2002) and only recently Cyanobacteria blooms have been reported to occur in lakes above the Arctic Circle (Kashulin et al. 2021). The highest latitude in Canada where an algal bloom has been mentioned in the literature is Great Slave Lake ~60°N (Pick 2016). With the exception of eutrophication caused by ancient whaling residues (Douglas et al. 2004), sewage and waste water (Rigler 1972, 1974; Kashulin et al. 2021), and more recently by increased geese and seabird populations (Michelutti et al. 2009; Hessen et al. 2017; Jensen et al. 2019), eutrophic lakes are rarely mentioned in the Arctic scientific literature. Higher temperatures and increased weathering and leaching rates may, however, push the lakes across the threshold above which eutrophication would be triggered. Out of 1280 analyzed Canadian Arctic lakes and ponds, about 8% can be classified as eutrophic based on their P content using Carlson’s Trophic State Index (Carlson 1977; Dranga et al. 2018).

The rapid environmental changes occurring in the Arctic make it imperative to gather more information and better understand high latitude lake properties and their potential responses to climate change, which are largely unknown. Here, we describe the current

Fig. 1. (a) Map of the Greiner Lake watershed, Victoria Island, Nunavut, Canada. Upper left panel shows Victoria Island with respect to the Canadian Arctic Archipelago. Lower left panel denotes the 35 sampled lakes and ponds (red dots). Right panel enlarges the red box outlined in the lower left panel and shows the main study site (ERA5) with Greiner Lake (GRL) in the lower left corner. Created with Q-GIS 3.14, based on Landsat 8 OLI imagery courtesy of the [U.S. Geological Survey \(2020\)](#), Canada administrative limits ([Natural Resources Canada 2020a](#)), Canada elevation data ([Natural Resources Canada 2020b](#)) and in situ GPS data. (b) View of lake ERA5 in July 2020. (c) Green-coloured water in the middle of lake ERA5.



trophic state of 35 water bodies in the Greiner Lake watershed, Victoria Island, Nunavut. We separated the water bodies into lakes and ponds based on their size, which affects their resilience to external nutrient inputs, and the presence or absence of fish, to account for differences in trophic state that may be associated with different food web structures and, hence, algal biomass ([Rautio and Vincent 2006](#)). In addition to measuring nutrients and standard limnological parameters, we characterized the dominant phytoplankton groups, in particular, Cyanobacteria, and measured bacterial production as a proxy of decomposition that would make organic P more available to phytoplankton ([Zhao et al. 2012](#); [Ger et al. 2014](#)), providing another indicator for eutrophication. We report on a specific eutrophic lake that was found amid oligotrophic lakes in the same watershed. The broader significance of the study is the contribution of contextual data on the current limnological state of freshwater ecosystems in the Arctic. This study draws attention to the importance of local differences in northern catchment–lake connections, and is a contribution to the project Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections (T-MOSAIC).

Materials and methods

Study site

The Greiner Lake watershed is located on south Victoria Island ($69^{\circ}10'35.72''\text{N}$, $104^{\circ}55'54.87''\text{W}$), Nunavut, contains an estimated 6280 lakes and ponds and covers nearly 1500 km^2 . The watershed is a source of both fish and potable water for the nearby Hamlet of Cambridge Bay, the fifth largest Inuit community in Nunavut with 1766 habitants in 2020 ([Fig. 1a](#)). The watershed is also currently the focus of wider ecosystem change studies by the Canadian scientific community in conjunction with the Canadian High Arctic Research Station.

Most of the lakes and ponds in the watershed are small (84% <5 ha) and shallow (99% <4 m deep). The larger lakes are always connected to the main watershed system and typically support fish populations consisting of varying combinations of Arctic Charr (*Salvelinus alpinus* (Linnaeus, 1758)), Lake Trout (*Salvelinus namaycush* (Walbaum in Artedi, 1792)), Lake Whitefish (*Coregonus clupeaformis* (Mitchill, 1818)), Least Cisco (*Coregonus sardinella* Valenciennes in Cuvier and Valenciennes, 1848) and Nine-spine Stickleback (*Pungitius pungitius* (Linnaeus, 1758)). In contrast, ponds are smaller and shallower and typically isolated systems. Thus, following Rautio et al. (2011), ponds were classified here as fishless water bodies, disconnected from other water bodies at the time of sampling, with an average depth <1 m and <10 ha in surface area.

Sampling and analyses

Single water and plankton samples were collected using a portable inflatable boat from 23 lakes and from the shore of 12 ponds in August 2018 and 2019. Lakes Greiner (GRL), 1ST, 2ND, ERA1, ERA4 and CBL5 were sampled in both years. Temperature, oxygen and conductivity profiles were measured in situ using a Ruskin RBR Concerto logger. Depth was measured using a depth sounder (Hawkeye DT1H) in both lakes and ponds. Water was collected from a single sub-surface depth in the ponds and up to five depths in lakes, using a 2 L Limnos closing water sampler (Limnos, Poland). Multiple casts were mixed in a clean 20 L bucket to make one composite sample. The collected water was immediately sub-sampled for total phosphorus (TP) and total nitrogen (TN) in individual acid-washed glass bottles. Two other subsamples were also filtered through a 0.45 µm syringe filter for total dissolved phosphorus (TDP) and dissolved organic carbon (DOC) and similarly stored in acid-washed glass bottles. Water for phytoplankton analysis was collected in 125 mL Nalgene bottles and preserved with 0.5 mL of 5% Lugol's solution. The remaining water was transferred to 4 L Nalgene bottles placed in a "cooler" and brought to the laboratory at the Canadian High Arctic Research Station by helicopter or all-terrain vehicle for Grenier Lake and close by lakes and ponds. Back at the laboratory, three replicates of 500 mL were immediately filtered through pre-combusted Whatman GF/F filters for chlorophyll *a* (Chl *a*) and stored frozen for later extraction. Bacterial production was measured immediately upon return from sampling using leucine incorporation following methods described by Kirchman (2001). Briefly, triplicate vials of 1.2 mL of unfiltered water were spiked with [³H]-leucine (30 nM final concentration) and incubated for 3 h at 10 °C ± 2 °C based on in situ measured temperatures (Table 1). Production after incubation was stopped using trichloroacetic acid (TCA, 50%). Two control vials with TCA were additionally prepared. Lake water and [³H]-leucine were added to the TCA solution allowing measures and subtraction of passive absorption of leucine by the bacteria. All vials were preserved at -20 °C until scintillation counting (see below).

TP, TDP, TN and DOC were analyzed by Environment and Climate Change Canada at the Burlington-National Laboratory for Environmental Testing following internal protocols (Environment Canada 2019). Chl *a* samples were extracted in 90% ethanol and analyzed spectrofluorometrically following Nush (1980). Bacterial production samples were concentrated by centrifugation at 12000 rpm to pellet the bacteria. The bacteria pellet was re-suspended in 1 mL scintillation cocktail and let sit for 24 h. Radioactivity was measured using a Perkin Elmer Tri-Carb 2910 scintillation counter. Phytoplankton were enumerated (counts) by microscopy by Biologica Environmental Services Ltd., Victoria, BC, Canada. Depending on the Chl *a* concentration of each lake, sub-samples from 3 mL (for highly concentrated samples) to 100 mL were analyzed after 24 to 48 h sedimentation in Utermöhl chambers (Lund et al. 1958). Counting was done using a Zeiss Axio Vert A.1 inverted phase contrast microscope at 400× magnification. All algal cells were counted in a series of

random fields of view until a minimum of 300 algal units were enumerated (Grace Analytical Lab 1994). Biovolume calculations were performed by measuring at least 10 cells of each taxon and applying the standard geometric formula with the best fit to the shape of the cell (Hillebrand et al. 1999). Finally, Landsat 5TM and 8 OLI imagery, courtesy of U.S. Geological Survey (2020), was used to compare the colour of ERA5 and adjacent lakes from 1989 to 2019. Satellite data were processed using Q-GIS 3.14. Each band was converted into apparent reflectance values and atmospherically corrected, re-projected into the NAD83 UTM Zone 13N coordinates system and displayed in RGB composition using the corresponding bands (Jensen 2016).

Data analyses

The Trophic State Index (TSI) classifies lakes according to their trophic state, using Chl *a*, Secchi depth or TP values (Carlson 1977). Lakes can be classified into 5 different categories: ultra-oligotrophic, oligotrophic, mesotrophic, eutrophic, and hypereutrophic (Carlson and Simpson 1996). The TSI for all lakes was calculated using eqs. 1 and 2 as proposed by Carlson (1977) using Chl *a* and TP values, respectively.

$$(1) \quad TSI(Chl\ a) = 10 \left(6 - \frac{2.04 - 0.68 \ln Chl\ a}{\ln 2} \right)$$

$$(2) \quad TSI(TP) = 10 \left(6 - \frac{\ln \frac{48}{TP}}{\ln 2} \right)$$

Phytoplankton community abundance structures (based on Bray–Curtis similarity) were compared between ponds and lakes using permutational multivariate analysis of variance (Anderson et al. 2008) run with 999 permutations. Prior to analyses the data sets were reduced from 109 to 44 taxa to retain species that contributed at least 5% of the total abundance found in a lake or pond and all data were square root transformed using shade plot methods (Clarke et al. 2014). PND4 was excluded from the analyses as it contained only one taxon, which made it an outlier in the analyses. Multivariate analyses and ordinations were run using PRIMER + PERMANOVA v.7 (Anderson et al. 2008; Clarke and Gorley 2015).

Results

A clear difference between lakes and ponds could be seen in the field, as lakes were well connected via rivers and streams. Ponds, by contrast, were disconnected, smaller, and had abundant large-sized zooplankton visible to the naked eye, which indicated a lack of significant vertebrate (e.g., fish) predation. The ponds also had an overall higher trophic status compared with the lakes, with 20% higher mean Chl *a* and TP, 30% higher TDP, 62% higher TN, 70% higher DOC and a 40% higher phytoplankton biovolume (Table 1). However, of the 35 lakes and ponds studied, TP values were higher in one lake (ERA5; 32.3 µg·L⁻¹) compared with any of the ponds. Lake ERA5 (Figs. 1b and 1c) also had the highest values for TDP (9.8 µg·L⁻¹), Chl *a* (4.29 ± 1.18 µg·L⁻¹), TN (940 µg·L⁻¹) and DOC (9.9 mg·L⁻¹) among the studied lakes (Table 1).

The TSI calculated for TP indicated that most lakes and ponds were oligotrophic or ultra-oligotrophic. Only three ponds were mesotrophic (PND3, PND8, and PND10) (Fig. 2a). However, lake ERA5 was classified as eutrophic based on its high TP value. Using the TSI for Chl *a*, most lakes and ponds were classified as oligotrophic, but some lakes (ERA5, CBL1, CBL2) and ponds (PND10, PND11, PND18) were classified as mesotrophic. Based on Chl *a* there was a single eutrophic pond (PND4), although it was classified as oligotrophic according to its P concentration (Fig. 2a).

Table 1. Limnological characteristics of lakes, ponds, and Lake ERA5. Area is the range of category for surface area of the pond or lake. Other values are mean \pm standard deviation of 23 lakes and 12 ponds.

	Unit	Lakes	Ponds	ERA5
Area	ha	4.31 – 3873.72	0.07 – 7.31	141.32
Depth	m	8.5 \pm 7.6	0.5 \pm 0.1	1.2
Chl a	$\mu\text{g}\cdot\text{L}^{-1}$	1.86 \pm 1.08	2.30 \pm 2.22	4.29
Temperature	$^{\circ}\text{C}$	10.0 \pm 1.0	10.0 \pm 2.1	8.7
Conductivity	$\mu\text{S}\cdot\text{cm}^{-1}$	378.0 \pm 185.3	549.3 \pm 250.6	682.7
TN	$\mu\text{g}\cdot\text{L}^{-1}$	425.8 \pm 163.7	1128.8 \pm 216.4	940.0
TP	$\mu\text{g}\cdot\text{L}^{-1}$	8.4 \pm 5.5	10.4 \pm 2.6	32.3
TDP	$\mu\text{g}\cdot\text{L}^{-1}$	5.8 \pm 1.3	8.4 \pm 1.7	9.8
DOC	$\text{mg}\cdot\text{L}^{-1}$	5.0 \pm 1.6	16.0 \pm 2.8	9.9
Bacterial Production	$\mu\text{g C}\cdot\text{L}^{-1}\text{d}^{-1}$	31.7 \pm 19.8	48.2 \pm 31.6	112.1
Total phytoplankton biovolume	$\text{mm}^3\cdot\text{L}^{-1}$	0.65 \pm 0.61	1.11 \pm 1.91	0.59
Chlorophyta biovolume	$\text{mm}^3\cdot\text{L}^{-1}$	0.04 \pm 0.04	0.12 \pm 0.14	0.19
Cyanobacteria biovolume	$\text{mm}^3\cdot\text{L}^{-1}$	0.02 \pm 0.05	0.04 \pm 0.09	0.25

Note: Chl a, chlorophyll a; TN, total nitrogen; TP, total phosphorus; TDP, total dissolved phosphorus; DOC, dissolved organic carbon.

Bacterial production values in lakes averaged $31.7 \pm 19.8 \mu\text{g C}\cdot\text{L}^{-1}\text{d}^{-1}$ and in ponds $48.2 \pm 31.6 \mu\text{g C}\cdot\text{L}^{-1}\text{d}^{-1}$ (Table 1). The ERA5 site ($112.1 \pm 7.6 \mu\text{g C}\cdot\text{L}^{-1}\text{d}^{-1}$) had the highest value among all studied water bodies.

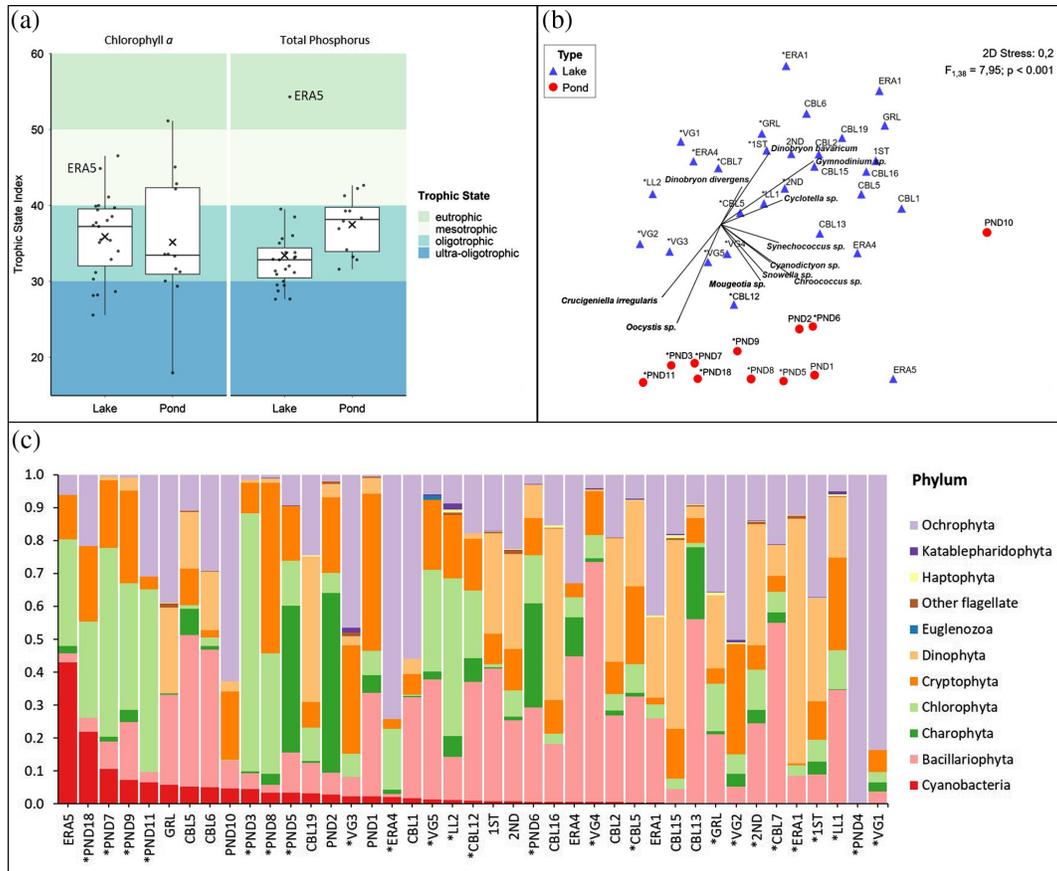
The non-metric multidimensional scaling (nMDS) analysis based on the taxonomy of phytoplankton category biovolumes showed a highly significant difference between lakes and ponds ($F_{1,38} = 7.95$; $p < 0.001$) (Fig. 2b). Although ERA5 is a lake because of its large surface area and connected to the main watershed drainage system, it grouped closer to the ponds (Fig. 2b). Nevertheless, there was a clear difference in the phytoplankton composition, especially in the greater proportion of Cyanobacteria found in ERA5 as compared with the other lakes and ponds (Fig. 2c). The biovolume of Cyanobacteria in ERA5 was greater than in any of the other 34 lakes and ponds and represented nearly 43% of the total phytoplankton biovolume in the lake (Table 1 and Fig. 2c). Four cyanobacterial genera were identified in ERA5, the most abundant was *Chroococcus* sp. (24.2%), followed by *Cyanodictyon* sp. (13.2%), *Snowella* sp. (5.3%) and *Synechococcus* sp. (0.2%). The second most represented group was Chlorophyta with 32.3% of the total biovolume and four genera: *Pediastrum* sp. (11.2%), *Planctonema* sp. (11.2%), *Oocystis* sp. (5.4%) and *Crucigenia* sp. (4.5%). Two other sites, both ponds, had higher than 10% representation of Cyanobacteria (Fig. 2c).

The satellite imagery suggested ERA5 has had an elevated trophic status for the last 30 years as evidenced by the constant light green color of the water through the years that contrasted with the darker blue color observed in Greiner Lake (Fig. 3). Other green, likely eutrophic, lakes in the Greiner watershed occurred in the same area, close to ERA5.

Discussion

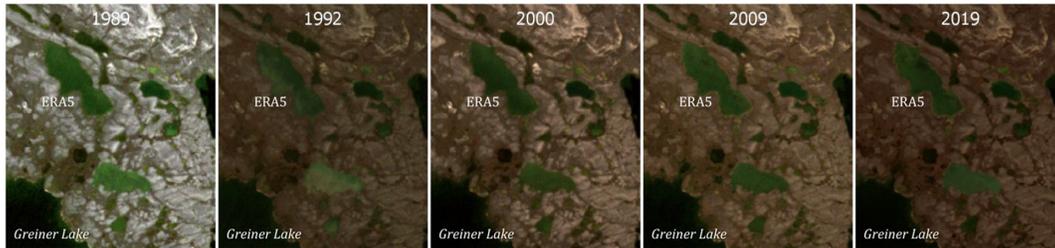
Lakes and ponds differed in their nutrient composition. A dilution effect in lakes appears to explain the lower nutrient concentration in larger water bodies as noted by Dranga et al. (2018), and is associated with larger surface area and depth. One lake, ERA5, however, was ranked as eutrophic according to both TP and Chl a, with a >40% prevalence of Cyanobacteria by phytoplankton biovolume. To our knowledge, this is the first time eutrophication from high TP and associated elevated Chl a concentrations has been reported in an Arctic lake without direct human impact. Interestingly, satellite imagery suggests other similarly high trophic state lakes are present in the same watershed (Fig. 3).

Fig. 2. (a) Trophic State Index calculated for chlorophyll *a* and total phosphorus for all lakes and ponds. Whiskers are 1.5 times the interquartile range. Means are represented by an X, medians by a line, and dots are data. (b) Non-metric multidimensional scaling plot representing the community structure in each pond/lake. Shown vectors of taxa were selected based on their contribution as % of the difference between ponds and lakes, and a few additional Cyanobacteria and Chlorophyta taxa were also included to illustrate the different communities observed in ERA5. (c) Proportions of phytoplankton phylum by biovolume in waterbodies, ordered by presence of Cyanobacteria. All pond names start with PND. Lakes and ponds that were sampled in 2019 are marked with an asterisk (*).



Lakes in the Arctic are typically classified as ultraoligotrophic or oligotrophic according to their TP values (Lyons and Finlay 2009). For Victoria Island, reported values from 95 lakes and ponds in previous studies have ranged from 0.01 $\mu\text{g}\cdot\text{L}^{-1}$ to 71 $\mu\text{g}\cdot\text{L}^{-1}$ (Dranga et al. 2018). P concentrations were high in six of these lakes and ponds located in the north of the island, but no other eutrophication indicators were reported. Hamilton et al. (2001) attributed the high values to the phosphorus-rich bedrock composition of the area associated with the volcanic formations at the northern end of the island (Williamson et al. 2013). The south of the island, near Cambridge Bay, sits over base-rich limestone till (McLennan et al. 2018) that tends to have lower P concentrations (Porder and Ramachandran 2013). Hamilton et al. (2001) also indicated that although TP values were high, the type of phosphorus present was bound to particles and inaccessible to phytoplankton. This suggests the P found in ERA5 may come from the organic upper layer of the soil. Reported Chl *a* concentrations for nine lakes in south Victoria Island, including Second Lake (2ND) analyzed in

Fig. 3. Satellite images from 1989 to 2019 (Landsat 5TM 1989-2009 and 8 OLI 2019) of ERA5, including a section of Greiner Lake. All images are from August, courtesy of the [U.S. Geological Survey \(2020\)](#) and processed with Q-GIS 3.14.



this study had a mean of $0.50 (\pm 0.47) \mu\text{g}\cdot\text{L}^{-1}$ ([Dranga et al. 2018](#)). TN values in the same database had a mean of $366 (\pm 170) \mu\text{g}\cdot\text{L}^{-1}$. Almost 20 years later, our results in the same area indicate Chl *a* and TN values higher than either of these earlier studies ([Table 1](#)). This result is consistent with other studies that have indicated that Chl *a* values appear to be increasing and freshwater ecosystems have become more productive as a result of the rapid climate-driven changes affecting the Arctic ([Michelutti et al. 2005](#); [Stuecker et al. 2018](#); [Hargan et al. 2020](#)). As Chl *a*, phytoplankton biomass, and nutrients are positively correlated with mean July temperature ([Dranga et al. 2018](#)), small increases in temperature in the Arctic can have a major effect, especially in shallow water bodies that have been shown to respond rapidly to shifts in air temperatures ([Rautio et al. 2011](#)).

Other mechanisms contributing to the higher trophic status include permafrost thaw and increases in hydrological connectivity associated to higher temperatures. Although no apparent changes in precipitation have taken place in the Cambridge Bay region for the last 50 years, temperatures have increased ([Environment and Climate Change Canada 2020](#)), contributing to deeper soil thaw in summer, and greening. Changes in catchment vegetation and the active layer modify the chemical composition of water that leaches out from soils rich in nutrients. Phosphorus and nitrogen supplements enter the lakes through water tracks and via passive transport ([Harms et al. 2019](#)), and stimulate primary production ([Wauthy and Rautio 2020](#)). Further, ERA5 is located on the northern section of the Greiner watershed in an area that has the highest snow accumulation in the region (on average 85 cm versus the mean 35 cm for the region; A. Langlois lab, personal communication, 2020). It could be that the greater volume of snowmelt in spring moves associated nutrients from the watershed to ERA5, thereby contributing to eutrophication. The green colour in the nearby lakes ([Fig. 3](#); E. Imbeau, personal communication, 2020) further suggests that the high snow accumulation on the north shore of Greiner creates favorable conditions for phytoplankton growth.

Another explanation for high nutrient values in ERA5 and in some of the ponds, may be the presence of geese in the area ([Jensen et al. 2019](#)). Six species of geese nest on Victoria Island: Snow Goose (*Anser caerulescens* (Linnaeus, 1758)), Ross's Goose (*Anser rossii* Cassin, 1861), Greater White-fronted Goose (*Anser albifrons* (Scopoli, 1769)), Brant (*Branta bernicla* (Linnaeus, 1758)), Cackling Goose (*Branta hutchinsii* (Richardson, 1832)) and Canada Goose (*Branta canadensis* (Linnaeus, 1758)) ([Hines et al. 2000](#); [Lok and Vink 2012](#); [Kerbes et al. 2014](#); [Canadian Wildlife Service Waterfowl Committee 2020](#)). The White-fronted Goose and Brant are reported to have had large population increases in Canada since the 1970s ([Canadian Wildlife Service Waterfowl Committee 2020](#)). Further, Snow Goose and Ross's Goose populations have increased across the Canadian Arctic to the point of being declared

overabundant in 2014 (Lefebvre et al. 2017; Canadian Wildlife Service Waterfowl Committee 2020). Geese foraging affects plant communities and their feces can change the chemical composition of soil and water, provoking eutrophication (Mariash et al. 2018). Bird feces were noted around most lakes and ponds, with higher concentrations found in and around shallower water areas (P. Blackburn-Desbiens, unpublished data, 2019). Feces are a source of TP and TN and can trigger cyanobacterial blooms (Jensen et al. 2019; Mariash et al. 2019), but residence time, dictated by geomorphology, would determine the likelihood of a persistent or annual recurring bloom. The area surrounding ERA5 is dominated by moderate slopes on the northern side of the lake and characterized by *Dryas integrifolia* Vahl – *Carex rupestris* All. plant associations that can range from 10% to 75% cover (Ponomarenko et al. 2019). The southernmost margin of the lake is dominated by two converging slopes and flat areas that are often flooded. *Carex* species are abundant and exposed to high levels of goose grazing and feces deposition, which increases nutrients in the soil and shallow waters (Ponomarenko et al. 2019) that are subsequently flushed to lakes, especially with high snowmelt.

The separation of lakes and ponds observed in the nMDS suggested an important difference in the phytoplanktonic composition between smaller, shallower water bodies and lakes (Fig. 2b, Supplementary Table S1¹). Phytoplankton in lakes were dominated by Dinophyta, Cryptophyta and Bacillariophyta, differentiating them from ponds where Chlorophyta were the most abundant taxa, as has also been shown elsewhere in the Arctic (Sheath 1986; Charvet et al. 2011). ERA5, despite its large surface area and lake-like pelagic food web structure with fish at the top of the food chain, clustered close to the ponds. It is possible that the zooplankton community in this shallow lake was more typical of that of ponds, with large-bodied cladocerans applying a high grazing pressure on phytoplankton and shaping its community composition (Rautio and Vincent 2006). More studies are required to accurately estimate the reasons for the phytoplankton community difference between ponds and lakes.

In subarctic ponds with Cyanobacteria, the richness and diversity of other phytoplankton species was generally low (Przytulska et al. 2017). As noted in Fig. 2c, other phytoplankton groups were also less predominant in lake ERA5 compared with Cyanobacteria. Although the Cyanobacteria identified by microscopy did not include N₂-fixing species with heterocytes, increasing temperatures may promote their growth in high latitudes in the future (Woolway et al. 2020). For example, cyanobacterial algal blooms in subarctic freshwaters were reported when water temperatures exceeded 15 °C during the summer (Gu and Alexander 1993; Gu et al. 1996; Pokrovsky and Shirokova 2013; Pick 2016). However, cyanobacterial blooms have not been reported in the High Arctic, even in sewage-impacted Meretta Lake on Devon Island (Rigler 1972, 1974), where temperatures have not reached 15 °C to date.

The cyanobacteria found in ERA5, notably *Synechococcus*, are considered picocyanobacterial taxa and are frequently found in Arctic freshwaters (Lizotte 2009; Vincent and Quesada 2012). However, the high biovolume proportions may have been an underestimate as, due to their small size (0.8–3.0 µm), conventional light microscopy routinely misses these small cells. The relatively low total phytoplankton biovolume in ERA5 is explained by the small sized cells, making the high biovolume of Cyanobacteria even more striking. Several small celled cyanobacterial groups, including the species of Chroococcales such as *Chroococcus* found in ERA5, are considered indicators of increasing P and high N concentrations (Andersson et al. 2015; Freeman et al. 2020) in addition to the green alga, *Pediastrum*,

¹Supplementary material is available with the article at <https://doi.org/10.1139/as-2020-0033>.

which was only found in ERA5, with a prevalence of 11.2% of phytoplankton biovolume (Supplementary Table S1¹). *Pediastrum* has been associated with increased primary production driven by recent climate change in subarctic and High Arctic lakes (Rühland et al. 2009; Woelders et al. 2018).

Further, the high values of bacterial production in lake ERA5 indicate heterotrophic bacteria were actively decomposing organic matter (Hobbie and Laybourn-Parry 2009) and likely contributing to the phytoplankton and, notably, the cyanobacterial biomass by converting unavailable organic P into dissolved available P. The high bacteria production was likely fueled by the high concentration of DOC (9.9 mg·L⁻¹), which was the highest among the lakes studied. The *Carex* beds along the shore of ERA5 were a probable source of this DOC. Although the role of macrophytes in carbon cycling is unknown in the Arctic, it is known from boreal lakes that macrophyte leachates are an important source of energy for bacterial production (Findlay et al. 1986), which subsequently provides nutrients to the system. The role of macrophytes as a DOC source is also supported by the high DOC concentration in ponds that are frequently surrounded by macrophytes.

In summary, higher concentrations of nutrients, Chl *a*, DOC, and bacterial production were more evident in ponds most likely due to their small size and isolated condition, which makes them highly responsive to nutrient and organic carbon inputs from the catchment as well as to increases in temperature. Although the relative contributions of the source inputs of the eutrophication process are still to be determined, our results also consistently point to a eutrophic lake ERA5 associated with high concentrations of nutrients and dissolved organic matter. Based on P concentrations, eutrophic conditions in lakes are already present in the Arctic in low numbers (Dranga et al. 2018). However, high P concentrations leading to high cyanobacterial dominance, without any apparent human impact, has not, to our knowledge, been previously reported for an Arctic lake. Interestingly, satellite imagery from ERA5 and nearby lakes and ponds suggests some sites have routinely had high Chl *a* concentrations for decades. This may also be related to the shallowness of the water bodies, as lakes and ponds with a light green colour found close to ERA5 (Fig. 3) correspond to depths of less than 2 m reported by Ponomarenko et al. (2019). We argue that catchment and lake characteristics make some shallow lakes more susceptible/less resilient to eutrophication that is caused largely by different catchment inputs. Climate change stimulating nutrient enrichment in Arctic ecosystems suggests that a number of lakes will be predisposed to further eutrophication as conditions warm. Hence, the need for future research to establish whether, and how, increases in lake trophic states will affect resident phytoplanktonic communities and the rest of the food web in Arctic lakes and their downstream waters.

Arctic eutrophication could also affect water quality and may require closer monitoring of drinking water sources. In addition, eutrophication could become more widespread in a changing climate, as other components of the ecosystem, such as geese populations, move or expand with increases in plant cover as temperatures warm. Arctic coastal landscapes often feature vast low-lying areas dotted by lakes and ponds that are culturally connected to local Inuit. The proximity and connectivity of ERA5 and other potentially eutrophic lakes to Greiner Lake makes it advisable to monitor the waters of both ERA5 and Greiner given the importance of the latter as a drinking water source for the Ikaluktutiak Inuit. Our results further suggest that upstream information from watersheds is needed to provide useful context for understanding future changes in larger downstream lakes currently supporting local fisheries, such as in Greiner Lake that receives water directly from ERA5. Although few Arctic limnological studies are conducted at the watershed scale, further investigation at such a scale, including studies on hydrological connectivity and paleolimnology, will provide an improved understanding of the processes driving Arctic lake trophic

status, more accurate nutrient source information and dating of the onset of lake eutrophication processes.

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