Title: Breeding eider ducks strongly influence subarctic coastal pond chemistry

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Abstract

Arctic freshwater ponds are typically pristine and oligotrophic, however, seabird biovectors can markedly alter water quality via enrichment with marine-derived nutrients and bioaccumulated metals. These ornithogenic inputs can be the dominant factor structuring aquatic biota and the surrounding island flora. Here, we measured a suite of limnological water chemistry variables and sediment geochemistry from 21 freshwater ponds influenced by Common Eiders (*Somateria mollissima*) in Hudson Strait, near the northern communities of Cape Dorset (Nunavut) and Ivujivik (Quebec). Nest counts and sedimentary $\delta^{15}N$ values were used as proxies of bird abundance. Nutrient-rich guano from the nesting eiders visibly promoted the growth of catchment vegetation. Elevated metal (Al, Cd, Zn), metalloid (Se), and nutrient concentrations (N, P) in the water of eider-affected sites were recorded (Sign test; $p = 0.004$), but the proximity of many sites to the coast meant that variables related to ocean spray (conductivity, Na^+, Mg^{2+}, Cl^-, Sr) confounded the effects of birds on pond water chemistry. In contrast, sediment geochemistry appeared to more clearly characterize sites according to the level of eider activity in their catchments by tracking Pb, Cd, N, and P sedimentary concentrations (Sign test; $p = 0.02$). These results have direct implications for reconstructing historical eider population trends using sediment archives, which is necessary to inform effective conservation management strategies.

Keywords: Ornitholimnology; biovector; Common Eider; Arctic; nutrients; metals

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Introduction

The study of Arctic lakes and ponds is logistically challenging, yet limnological research at high latitudes remains active primarily due to the sensitivity of Arctic freshwaters to global change (Smol and Douglas 2007; Rühland et al. 2008; Kaufman 2009; Smol 2016). One emerging field of study, ornitholimnology (Hurlbert and Chang 1983), investigates the influence of bird colonies on freshwater systems. Seabirds are potent biovectors, meaning they are capable of transporting and focusing nutrients (and contaminants) from their marine feeding grounds to their terrestrial nesting sites largely via their nutrient-rich feces and other deposits, eggshells and carcasses (Bildstein et al. 1992; Blais et al. 2007). In naturally oligotrophic Arctic regions, the nutrients and contaminants transported by biovectors greatly modifies the recipient terrestrial and aquatic ecosystems. For example, Blais et al. (2005) describe a 25-fold enrichment of total Hg and a 60-fold enrichment dichlorodiphenyltrichloroethane (DDT) to the environment derived from a Northern Fulmar (*Fulmarus glacialis*) colony in Cape Vera, Nunavut. Seabirds are one of the most prolific biovectors on the planet, with breeding seabirds producing and concentrating an estimated global excrement input onto land of 591 Gg N/y and 99 Gg P/y (Otero et al. 2018) and a total global input from all seabirds of 3800 Gg N/y and 631 Gg P/y (Otero et al. 2018). The total seabird input of N and P is comparable to estimates of the total nutrient input inland from the sea via global fisheries (N = 3700 Gg/y, Maranger et al. 2008; P = 320 Gg/y, Mackenzie et al. 1993). The effect of N and P loading cannot be understated as avian guano is a driving factor in shaping many biological communities, including floral (Zwolicki et al. 2013; Otero et al. 2015) and faunal (Sánchez-Piñero and Polis 2000; Zhu et al. 2015) assemblages. Because seabirds markedly alter the nutrient composition of the water chemistry and sediment geochemistry of their environment (Evenset et al. 2004; Blais et al. 2005; Keatley et al. 2009), paleolimnology can be used to infer population presence (Stewart et al. 2015), trends (Luoto et al. 2014), and dynamics through time (Keatley et al. 2011). By determining the historical population dynamics of a species, more effective conservation strategies can be implemented to sustain extant populations.

Common Eiders (*Somateria mollissima*) are the largest duck in the Northern Hemisphere, inhabiting coastal marine Arctic and subarctic environments (Goudie et al. 2000). Most Common Eiders in the Arctic are migratory, although some may reside year-round and principally feed on molluscs and crustaceans (Goudie et al. 2000). Eiders nest in colonies, reusing previously built nests (Goudie et al. 2000). Once eggs are laid, female eiders spend > 99% of their time on the nest (Mallory 2015), presumably to provide warmth and to prevent egg predation. However, eiders must drink freshwater, therefore it is advantageous to build nests near inland ponds to minimize time away from the nest (Fast 2006). Due to their gregarious nature, as well as the proximity of their nests to freshwaters, Common Eiders are ideal study organisms in ornitholimnological investigations.

Here, we focus on the Northern Common Eider (*S. m. borealis*; hereafter eider), a subspecies that breeds along the coastline of the eastern Canadian Archipelago and winters along southwest Greenland through Newfoundland and Labrador (Mosbech et al. 2006; Steenweg et al. 2017). This subspecies prefers to build its nests on small, exposed, low-lying flat islands with small amounts of cover (Schmutz et al. 1983; Goudie et al. 2000). Many of these islands support small, freshwater ponds, which were the targets for our investigation. However, given the proximity of marine waters to the ponds and nest sites, we expected that ocean spray variables (conductivity, major ions and Sr, a trace metal highly associated with ocean spray) may confound variables related to eider influence, therefore we determined if other elements in the sediments more effectively track eider presence. Annual eider inputs to the same islands and nesting sites, including guano, eggshells, moulted feathers and carcasses, continually fertilize the soil around their nests with nutrients and potentially metals and other contaminants, which inadvertently also fertilizes the nearby pond catchment, water, and sediments (Mallory et al. 2006; Brimble et al. 2009a; Keatley et al. 2009; Mallory et al. 2015, Clyde 2016).

To quantify the influence of eider presence on the subarctic islands, we measured limnological water chemistry and sediment geochemistry of 21 ponds on islands in Hudson Strait influenced to varying degrees by eiders. The amount of eider activity in the catchments was estimated by direct counts of the active nests on each island and by using stable isotopes of nitrogen ($\delta^{15}N$) in surface sediments, a well-established proxy for tracking marine nutrients in freshwaters (Minagawa and Wada 1984; Kelly 2000; Michelutti et al. 2009). Additionally, the guano of eiders was analyzed to determine the direct elemental inputs and isotopic signature. Principal component analysis (PCA) was used to graphically visualize the main patterns of variation in the study sites in relation to the water chemistry variables and sediment geochemistry. We hypothesized that eiders act as biovectors and ecological engineers (like dovekies *Alle alle*, González-Bergonzoni et al. 2017) and that their breeding activity alters the terrestrial and freshwater habitats. Consequently, we predicted that ornithogenic markers (e.g., $\delta^{15}N$, Pb, Zn, P) would be enriched in water and/or sediment samples of the high influence ponds compared to low influence sites. This study is the first ornitholimnological investigation in the remote Hudson

Strait region and has direct implications towards reconstructing long-term eider population dynamics using sediment records from the ponds.

Study area and site selection

Cape Dorset (Nunavut, Canada) and Ivujivik (Quebec, Canada) are remote communities in the westerly arm of Hudson Strait (Fig. 1). Both areas have several nearby small uninhabited islands on which eiders nest. The two study regions exhibit similar geography and topography, both categorized as the Meta Incognita ecoregion (Sanborn-Barrie et al. 2008). The area is characterized by continuous permafrost and rugged bedrock, with minor amounts of colluvial soils (3vGeomatics 2011). Natural vegetation is dwarfed due to high winds, frigid temperatures and poor soils (Ricketts et al. 1999). Sampling locations were given unofficial names by the monitoring program at Environment Canada and Climate Change (ECCC). Sites A036 to A136 were ponds near Cape Dorset, and sites D003 to D022 were ponds near Ivujivik (Fig. 1). Sampling locations were the main pond of each island, and islands were selected on the basis of previous eider colony surveys, attempting to encompass a range of eider abundance (Clyde 2016). Site D018 was a nearly abandoned eider colony with few remaining eiders, taken over by a large number of gulls, outnumbering the number of eider nests of the other sampled islands. Large Arctic gulls occupy high trophic levels and are opportunistic feeders that consume a variety of foods, including fish, eggs and carrion (Mallory and Braune 2012). Since site D018 had a larger population of the gulls than eiders (which occupy lower trophic levels), site D018 was expected to have higher concentrations of metals (Portnoy 1990; Michelutti et al. 2009). Site D019 was particularly close to the ocean and received large amounts of ocean spray, and therefore was expected to have higher levels of aqueous marine ions, such as Na^+, Mg^{2+}, Cl^-, as well as Sr compared to the study sites located farther inland (Côté et al. 2010; Chagué-Goff 2010; Hargan et al. 2017). Certain physical characteristics of the sample islands were measured post-hoc, including surface area using Google Earth ©2018 and distance to shore, which was measured from the centre of the pond to the nearest shoreline, accurate to 10 m (Government of Canada 2016).

Materials and methods

1. Sample collection

Ivujivik surface sediments and water chemistry samples were collected from nine island ponds between July 25-30, 2014, and Cape Dorset samples were collected from 12 island ponds between July 17-25, 2015. Approximately 1 L of surface water (< 1 m depth) and a single sediment core were collected from each pond, and sampling occurred once per pond. For metal analysis, approximately 300 mL of water was filtered using Sartorius© 47 mm polycarbonate filters with 0.4 µm pore size and kept in the dark at 4°C until analysis. For chlorophyll-*a* determination, 47 mm Whatman© glass microfibre filters were pre-ashed at 450°C for 12 h, then 500 mL of water was filtered. The filters were transferred to Petri dishes, wrapped in aluminum foil, and then stored frozen in the dark until sent to National Laboratory for Environmental Testing (NLET; Burlington, ON). Upon return to the lab, the water filtered for metal analysis was acidified to a pH < 2 and all water samples were sent to NLET to be analyzed for major ions, nutrients, and trace metals using standard procedures (Environment Canada Manual of Analytical Methods 1994a, 1994b). Specific conductivity and pH measurements were taken on-site using a calibrated YSI meter (Xylem, USA), and Hanna® handheld pH meter (USA), respectively. Temperature and pH were not collected in 2015 due to meter malfunction and therefore omitted from analyses (See supplementary table S1). Concurrently, sediment cores were retrieved using a high-resolution push corer (Glew and Smol 2016) and sectioned onsite at 0.5 cm intervals using a Glew (1989) extruder. Only the surface 0.5 cm interval, representing the most recent conditions, was used in sedimentary geochemistry and δ^{15}N analyses. Eider guano samples were collected from eiders that defecated while being handled by ornithologists and analyzed independently.

2. Elemental analysis

Samples were prepared following standard methodologies (SGS Canada Inc. 2014). Briefly, freeze-dried sediment and guano samples from two eiders were pulverized in an agate bowl and then subjected to an aqua regia digestion to extract the environmentally relevant metals while preserving the silicate matrix. Inductively coupled plasma mass spectrometry was used to analyze 30 elements of the sediment and guano: Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Se, Sn, Sr, Ti, Tl, U, V, Y, and Zn. Quality assurance and control were ensured by running certified reference material, internal standards, blanks, and duplicates after every batch of 20 samples. Analyses were carried out by SGS Canada in Lakefield, Ontario, with results certified by the Canadian Association for Laboratory Accreditation Inc. (CALA).

3. δ^{15}N stable isotopes

Nitrogen elemental and isotopic analyses of all samples were performed at the G.G. Hatch Stable Isotope Laboratory at the University of Ottawa, Ottawa, ON. For elemental %N analysis, sediment samples and standards were analyzed using a Vario EL III Elemental Analyzer (Elementar, Germany) following methods described in Brazeau et al. (2013). Sediment amounts needed for the $\delta^{15}N$ isotopic analyses were determined based on the results of the elemental analysis and weighed accordingly into tin capsules with two parts tungsten trioxide (WO_3). The isotopic composition of nitrogen was determined by the analysis of N_2, produced by combustion on a VarioEL III Elemental Analyzer (Elementar, Germany) followed by “trap and purge” separation and on-line analysis by continuous-flow with a DeltaPlus XP Plus Advantage Isotope Ratio Mass Spectrometer coupled with a ConFlo II (Thermo, Germany). Our $\delta^{15}N$ data were reported using delta (δ) notation in parts per thousand (‰) enrichments or depletions relative to common standards (AIR for $\delta^{15}N$). Isotope data were normalized using previously calibrated internal standards, and analytical precision was ± 0.2% (Pella 1990).

4. Quantifying eider influence

To evaluate the influence of eiders on each pond, we used the number of occupied nests on the island, as well as $\delta^{15}N$ values from the surface sediments of each site. Prior to fieldwork, the number of nests on each island were determined from unpublished field surveys conducted by ECCC and were used to approximate the number of eiders inhabiting the island (Clyde 2016). Due to the inconsistency of survey years, ranging from 1997-2012, the possibility of eiders abandoning their nests between years, and the opportunity of migratory birds utilizing the islands as stopovers, sedimentary $\delta^{15}N$ was used in conjunction with nest counts. Sedimentary $\delta^{15}N$ has been shown repeatedly to be elevated in soils and sediments receiving marine-derived nitrogen, and a faithful indicator of seabird inputs (Mizutani et al. 1986; Blais et al. 2005; Brimble et al. 2009a). $\delta^{15}N$ is enriched by approximately 3.4‰ per trophic level (Minagawa and Wada 1984), and therefore molluscivorous eiders introduce elevated levels of $\delta^{15}N$ via their guano to the otherwise low $\delta^{15}N$ freshwater environment (Michelutti et al. 2010). Further, due to biological processes, ocean water has a higher natural abundance of $\delta^{15}N$ than terrigenous or freshwater habitats (Montoya 2007), therefore ocean spray will elevate pond $\delta^{15}N$.

Based on the above qualifiers of active nest counts and $\delta^{15}N$, sites were divided into four categories: reference, low, moderate and high influence. Low influence sites had few active nests (≤ 10 per island) and low $\delta^{15}N$ (≤ 6‰). All other sites were split into moderate or high influence ponds, dependant on whether they were higher or lower than $\delta^{15}N$ = 10‰, the average level of eider guano (Clyde 2016). Based on this categorization, increasing number of nests was generally related to increasing $\delta^{15}N$. The main exception was A038 that was categorized as high influence (active eider nests = 7, $\delta^{15}N$ = 12.3), which may have elevated $\delta^{15}N$ due to migratory gull and/or goose populations, evidenced by droppings around the catchment of the pond. This highlights the importance of using an independent ornithological measurement, such as $\delta^{15}N$, to confirm nest or bird counts. As explained earlier, the gull colony pond and ocean spray reference sites, D018 and D019, were determined to qualify the effects of ornithological and ocean spray influence.

5. Statistical techniques

Principal component analysis (PCA) was used to summarize the relationship of study sites to measured environmental variables. Water chemistry variables that had > 10% below the detection limit (DL) were removed. Otherwise, if < 10% of measured variables fell below DL, they were approximated using DL of variable/square root(2) (Hornung and Reed 1990). Variables that were right skewed were normalized with a log(x+1) transformation. Parameters were then tested for normality with a Shapiro-Wilk test ($\alpha = 0.05$) (Shapiro and Wilk 1965), and nonparametric variables were eliminated. Redundant variables were identified with a Pearson correlation matrix ($p \leq 0.05$) with Bonferroni-adjusted probabilities using SPSS (See supplementary table S2, S3) (IBM SPSS Statistics for Windows, Version 19). A PCA of the correlated variables was used to determine a single variable that explained the largest amount of variation along the primary axis to represent the group. All ordination analyses were performed in Canoco, version 5.0 (ter Braak and Šmilauer 2012). A sign test is a nonparametric analysis that was used to determine if ornithological tracers (i.e. Al, As, Cd, Pb, Se, Zn, P, TN-F) were elevated in high influence ponds compared to low influence ponds. The test is well suited for small datasets to determine if the difference in medians is zero (Conover 1999).

Data treatment

1. Water ordination

Arsenic, Cd, Cl^-, K^+, Mg^{2+}, Na^+ and total phosphorus unfiltered (TP-UF) were eliminated from the ordinal analysis due to skewness from a normal unimodal distribution. Other than dissolved inorganic carbon (DIC), Cu and Pb, all variables were normalized with a log(x+1) transformation. Conductivity, major ions (Ca^{2+}, SO_4^{2-}) and Sr were correlated (See supplementary table S2) and represented by conductivity, which explained the largest amount of variation. Calcium and SO_4^{2-} are major ions that contribute to conductivity, and Sr is a trace metal highly associated with ocean spray (Chen et al. 1997; Wang and Zhai 2008; Chagué-Goff 2010). To constrict ordination results to reflect only the distribution of eider sites relative to water chemistry and sediment geochemistry, the gull colony and ocean spray ponds, D018 and D019, were plotted passively.

2. Sediment geochemistry ordination

Six sedimentary variables (As, Bi, Li, Sb, Se, Sn) were removed due to a large amount of below detection values. All variables other than Cd and Pb were normalized with a log(x+1) transformation, however, Be, Ca^{2+}, Mg^{2+}, Mo, Na^{+}, Th and U were eliminated from further analysis due to skewness. Trace metals, including Al, Ba, Co, Cr, Cu, Fe, Ni, Ti and V, were all correlated (See supplementary table S3), and therefore grouped by Al, which explained the largest amount of variation. Similarly, Cd and Zn were also correlated due to their binary relationship (Tang et al. 2014) and represented by Zn. Zinc has stable geochemistry in sediments (Boyle 2001) and is correlated with seabird inputs (Brimble et al. 2009b; Foster et al. 2011). Similar to the water ordination, the gull colony and ocean spray pond, D018 and D019, were plotted passively.

3. Statistical limitations

There were statistical limitations in this study due to the difficulty of locating and sampling islands with ponds with varying degrees of eider presence. This, compounded with finding sites that had similar geology and pond morphology, resulted in a limited sample size of 21 ponds, with a narrow range of eider populations. For this reason, there were too few samples to normalize several variables for PCA. However, of the removed variables, Cl^{-}, K^{+}, Mg^{2+}, Na^{+} are all major ions correlated to conductivity, which was represented on the water PCA. Additionally, the removed ornithogenic markers (As, Cd, TP-UF) were represented by other bird influence markers, including Pb and chlorophyll-*a*.

Results and discussion

1. Guano and physical characteristics

Given the proximity of the study ponds to each other and their similar morphometries (Table 1), variability related to site-specific differences such as geology, climate, and atmospheric deposition was minimal. Thus, the main factor influencing pond chemistries was presumed to be the varying abundances of eiders at each site. As has been shown previously, seabird guano fertilizes and modifies freshwater ponds and their catchments (Mallory et al.

2006; Brimble et al. 2009a; Côté et al. 2010). Guano is high in P, constituting 0.9-17% of excrement total mass (Otero et al. 2015). The guano samples analyzed from two eiders had P concentrations of 980 ± 170 µg/g (Table 2), which likely fertilized the catchment because sites that had high eider abundance also had visibly more catchment vegetation compared to the catchments of unaffected sites, which were bare rock (Fig. 2). Eiders prefer to build their nests in vegetation, using plant material and their down feathers to insulate their eggs and avoid harsh conditions (Goudie et al. 2000). This likely forms a mutualistic feedback loop, in which eiders return to vegetated areas, which they ultimately fertilized, and continue to support plant material via nutrient-rich waste products.

Ornithogenic elements analyzed in the guano, including Al, Cd, Pb and Se, were more elevated in the water and sediment chemistry of high influence ponds relative to low influence ponds (Table 3, 4), emphasizing the pronounced ornitholimnological effect of eiders. Eiders bioaccumulate trace metals due to their preference to feed on molluscs and benthic crustaceans, which are typically enriched in Al, Cd, Pb and Zn (Szefer et al. 2006) or their propensity to acquire Pb from hunting activities (Hicklin and Barrow 2004; Falk et al. 2006; Johansen et al. 2006). In eiders, elements bioaccumulate due to persistence and their inability to biodegrade (Cardwell et al. 2013). The elevated elements are released back to the ecosystem through guano, eggshells and carcasses.

2. Pond water chemistry

Elevated major ions and ornithogenic elements were recorded in the water of the eider-affected sites. In our 21-pond dataset, the gull colony reference pond, D018, had the highest measured metals of ornithogenic influence, as also described by Brimble et al. (2009b), including: As (8.45 µg/L), Cd (0.199 µg/L), Se (1.6 µg/L) and Zn (17 µg/L) (Table 3). Additionally, D018 had the highest concentrations of variables linked to eutrophication, and thus eider and/or gull influence, including: chlorophyll-*a* (429 µg/L), TP-F (3800 µg/L) and TP-UF (7100 µg/L) (Table 3). In our dataset, the ocean spray reference pond, D019, had the highest concentrations of major ions including: conductivity (13000 µS/cm), Ca^{2+} (133 mg/L), K^+ (116 mg/L), Mg^{2+} (357 mg/L), Na^+ (3350 mg/L) and SO_4^{2-} (862 mg/L) (Table 3). Moreover, D019 had the highest Sr (3180 µg/L), which is strongly associated with ocean spray (Chen et al. 1997; Wang and Zhai 2008; Chagué-Goff 2010).

The ornithogenic bioaccumulated elements were elevated in the water of the high eider-influence ponds compared to low influence ponds. Examples of such metals and metalloids include Al (low influence: 28.2 ± 11.8 µg/L, high influence: 93.8 ± 70.7 µg/L), Cd (low influence: 0.031 ± 0.031 µg/L, high influence: 0.047 ± 0.032 µg/L), Se (low influence: 0.19 ± 0.16 µg/L, high influence: 0.23 ± 0.19 µg/L) and Zn (low influence: 1.7 ± 0.57 µg/L, high influence: 2.7 ± 1.1 µg/L). Though comparisons of individual elements were not statistically significant due to a limited sample size, mean values of all eight identified ornithogenic tracers (Al, As, Cd, Pb, Se, Zn, P, TN-F; Mallory et al. 2004; Michelutti et al. 2010) were greater in the waters of the moderate and high influence ponds compared to low influence (Sign test; *p* = 0.004). Some of these elements were highlighted by Brimble et al. (2009b) as ornithogenic metals of concern, and potentially toxic. However, at the time of measurement, the elements were below the chronic level of concern in freshwater as per the Water Quality Guidelines for the Protection of Aquatic Life set by the Canadian Council of Ministers of the Environment (CCME) (Cd: 0.09 µg/L; Se: 1 µg/L; Zn: 30 µg/L). Further, these metals are considered guano-derived, and would not normally be elevated in pristine, unaffected ponds (Roberts et al. 2017), additionally supporting the marked influence of eiders on their environment.

Similar to metals, nutrients were elevated in eider-affected sites relative to control ponds (Table 3). As expected, measured phosphorus in the water was high, similar to other Arctic seabird studies (e.g. Keatley et al. 2009; Côté et al. 2010). In a 2001 study of nutrients in the Canadian Arctic Archipelago, the mean TP-UF of unimpacted lakes was 12 ± 18 µg/L (Hamilton et al. 2001). Although the low influence ponds had a mean TP-UF of 102 ± 1.4 µg/L, the high influence sites recorded a mean value four times greater at 416 ± 408 µg/L. The elevated P concentration in the low influence sites indicates that there is likely an additional source of phosphorus. Although the control sites currently do not have a large eider population, it is possible that seasonal migratory geese or gull populations land at the islands for short stopovers, evidenced by geese droppings across the islands. Geese are known to release a substantial amount of P in the Arctic via their feces (Mariash et al. 2018), from which the detectable reintroduction can last several decades (Søndergaard et al. 2003). Additionally, high δ^{15}N sites with few eider nests (e.g. A038) support the possibility of transient bird populations.

Total filtered nitrogen (TN-F) was also measured to determine the amount of organic N in the water, which has been shown to increase due to biovectors (Marion et al. 1994; Zwolicki et al. 2013). We measured a TN-F of 1.61 ± 1.06 mg/L in the low influence ponds and 3.98 ± 7.52 mg/L in high influence ponds (Table 3). Nitrogen, along with P, is associated with the growth and abundance of algal communities (Smith 1982) and can be linked to elevated chlorophyll-*a* concentrations in the eider ponds (low influence: 19.3 ± 1.13 µg/L; high influence: 22.0 ±

25.8 µg/L). The elevated TN-F in the eider affected ponds further highlights the ability of eiders to shape their environment.

In the Arctic, it is difficult to find control ponds with no bird influence because suitable habitat is limited, therefore every island is likely occupied and influenced by some bird presence during either migration or breeding seasons. Even sites with few active eider nests (e.g. A036, A038, D007) had higher P and $\delta^{15}N$ than would be expected if there were no birds present (Brimble et al. 2009a). This highlights the importance of independent proxies, such as $\delta^{15}N$, to corroborate nest or bird counts. Without controls, biogenic enrichment factors (Brimble et al. 2009b) to quantify the enrichment of affected sites due to guano subsidies were not developed. This limitation made comparisons between high and low influence sites statistically imperfect.

The PCA axes 1 and 2 explained 48.4% of the total variation with eigenvalues of $\lambda_1 = 0.294$, and $\lambda_2 = 0.190$ (Fig. 3). Axis 1 was strongly characterized by a Pb and dissolved organic carbon (DOC) gradient, which we consider to track the influence of eiders. As seen in other studies, eiders commonly have elevated Pb in their liver (Mallory et al. 2004), which is attributed to shot birds that survive and ingested lead shot leftover from hunting (Flint and Grand 1997; Franson et al. 2000; Grand et al. 2002). Additionally, eiders are molluscivorous, feeding on mussels and other benthic crustaceans (Goudie et al. 2000). Since molluscs are filter feeders, they concentrate Pb from the sediments (Szefer et al. 2006), which may be a minor contributor to Pb elevation in eiders, despite the inability of Pb to biomagnify (Cardwell et al. 2013) and evidence for biominification (Jenkins 1980). As the Pb is not metabolized, it is eventually excreted into the catchments of the study ponds (Mallory et al. 2010; Michelutti et al. 2010). In alkaline waters (pH > 7.5), like the water in this study, Pb complexes to form the insoluble $PbCO_3$, which is very stable and persistent in sediments (Long and Angino 1977). Dissolved organic carbon in water is largely related to vegetation (Neff and Hooper 2002), and thus aqueous DOC would be largely allochthonous in origin. There are also autochthonous sources of DOC via aquatic algal cell death and senescence, grazing, viral lysis and extracellular release (Bertilsson and Jones 2003). The study ponds had high productivity as evidenced by the elevated chlorophyll-*a* concentration compared to other Canadian Archipelago ponds (mean = 0.55 µg/L; Hamilton et al. 2001). Therefore, DOC in the highly influenced eider ponds will be elevated likely due to allochthonous eider guano fertilization and enhanced growth of mosses, as well as autotrophic algae. Importantly, increased DOC may influence the aquatic biota composition by limiting primary production (Carpenter et al. 1998), affecting both epilimnetic (Hanson et al. 2003) and hypolimnetic respiration (Houser et al. 2003) and increasing metal toxicity (Evans et al. 2005). The secondary axis was characterized by a gradient of conductivity, which is explained primarily by ocean spray. Ocean spray can strongly influence the water chemistry of nearshore Arctic ponds (Rühland and Smol 1998; Michelutti et al. 2002; Antoniades et al. 2003).

3. Sediment geochemistry

The sediment geochemistry of the study ponds also tracked the effects of eiders. The gull pond reference site, D018, had the highest measured P (16 mg/g) and As (6.9 µg/g), both of which are elements associated with high bird influence (Bildstein et al. 1992; Brimble et al. 2009b). Ocean spray variables that were elevated in the water chemistry (Ca^{2+}, Mg^{2+}, Na^{+} and SO_4^{2-}) were not increased in the sedimentary geochemistry of the ocean spray pond, D019. Most ions (Mg^{2+}, Na^{+}, SO_4^{2-}) are likely elevated in the sediment due to the underlying geology as opposed to water chemistry and allochthonous sources (Lent 1994), indicating that the effects of ocean spray on tracking biovectors in water do not translate to the sediments. Calcium in sediments may be elevated from guano and uneaten mussel shells (Öst and Kilpi 1998; Ebert et al. 2013). Potentially toxic trace metals and elements known to bioaccumulate in seabirds (Braune et al. 1999; Brimble et al. 2009b) were elevated in high influence relative to the low influence sites, including Al (low influence: 110 ± 830 µg/g; high influence: 3100 ± 4200 µg/g), Cd (low influence: 0.38 ± 0.48 µg/g; high influence: 2.0 ± 1.2 µg/g), Se (low influence: 1.1 ± 0.49 µg/g; high influence: 1.8 ± 0.93 µg/g), and Zn (low influence: 33 ± 32 µg/g; high influence: 96 ± 46 µg/g) (Table 4). As with the water chemistry, these comparisons were not statistically significant for each element due to low sample sizes. However mean values of all ornithogenic tracers (Al, As, Cd, Pb, Se, Zn, P) were higher in sediments of high and moderate influence ponds relative to low influence ponds (Sign test; $p = 0.02$). Additionally, many of these elements (As, Cd, Se, Zn, P) are considered guano-derived and would not normally be found elevated in the environment (Roberts et al. 2017). As with the water chemistry, sedimentary metals were far below the probable effect level of concern in sediment set by the CCME. Given that eiders occupy a relatively low trophic level, feeding on filter-feeding molluscs, there is minor metal accumulations compared to other Arctic marine birds. Our results are consistent with earlier work describing species-specific differences in the effect of Arctic avian biovectors, dependent on their trophic position (Michelutti et al. 2010). Considering the increased concentrations of ornithogenic tracers in high influence sites compared to low influence sites, and the high metal concentrations in the guano, we conclude that sediment geochemistry is tracking the ornithogenic inputs.

Elemental phosphorus was also elevated in the sediment of the ponds highly affected by eiders (low influence: 2.0 ± 2.4 mg/g; high influence: 4.0 ± 1.9 mg/g). Phosphorus in seabird guano constitutes 0.9-17% of total excrement mass (Otero et al. 2015). Following this trend, we measured high P in eider guano, which no doubt contributes to the long-term eutrophication and fertilization of the island and ponds (see Fig. 2).

Axes 1 and 2 of the PCA explained 51.6% of the total variation with eigenvalues $\lambda_1 = 0.311$, and $\lambda_2 = 0.205$ (Fig. 3). The first axis was characterized by a combination of eider influence (K^+) and ocean spray (Sr). Potassium is both bioenriched in sediments due to birds (Brimble et al. 2009a), as well as a major ion in ocean water. The secondary axis showed a strong gradient of Sr, which is associated with sea spray (Chen et al. 1997; Wang and Zhai 2008; Chagué-Goff 2010). Importantly, ornithogenic variables oriented together, including $\delta^{15}N$, Pb, Zn and P (Fig. 3). This reflects the elevated $\delta^{15}N$ and metal concentrations typical of seabird guano. As discussed above in the pond water chemistry section, Pb would be expected to be elevated due to hunting and in part prey preference. Zinc is an essential element that has the potential to be toxic in waterfowl (Beyer et al. 2004) and may be elevated in eiders (Burger and Gochfeld 2008; Lovvorn et al. 2013; Mallory et al. 2014). Zinc is a robust ornithogenic tracer due to its stability in sediments (Boyle 2001) and strong independent correlation to seabird inputs (Brimble et al. 2009b; Foster et al. 2011). Finally, P, as described above, was oriented with other ornithogenic variables. This is due to the high P concentrations in eider guano, washing into the pond from the nest.

Conclusions

Our study characterized the water chemistry and sediment geochemistry of 21 ponds influenced by eiders inhabiting Hudson Strait and demonstrated a pronounced ornitholimnological influence of the eiders. Proxies of ornithogenic influence, including Pb, bioaccumulated high-trophic metals (Al, Cd, Zn), metalloid (Se), and nutrient concentrations (N, P), were all higher in ponds with larger eider abundances than ponds with few or no eiders, consistent with earlier studies on the influence of various bird species on pond chemistry (Brimble et al. 2009a, 2009b; Michelutti et al. 2009; González-Bergonzoni et al. 2017; Roberts et al. 2017). Consequently, these ornithogenic variables support the hypothesis that eiders act as ecological engineers and biovectors, thus having the potential to structure the biota of the islands, as was reflected in much greater chlorophyll-*a* levels. Also, we determined that sediment geochemistry appears to better record ornithogenic variables than water chemistry because it tracks major ornithogenic proxies, including $\delta^{15}N$, Pb, Zn, and P. Since sedimentary geochemistry appears to faithfully track ornithogenic enrichment, this research provides additional evidence that downcore paleolimnological analyses are key tools for garnering insights into the timing of seabird arrival, colony growth and possible extirpation; information critical for conservation management. These data are key in understanding population and colony dynamics in areas for which data are typically sparse or logistically difficult to acquire.

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Tables and Figures

Table 1 Locations and physical variables of the 21-pond set, as well as the number of active Common Eider nests on each island in the most recent survey year, with corresponding surface sedimentary $\delta^{15}N$. Ponds are organized by influence, first reference ponds (Ref.), then low, moderate (Mod.), and high influence.

Influence	Pond	Official island name	Latitude (N)	Longitude (W)	Distance to shore (m)	Island surface area (km^2)	Nests (year)	δ^{15}N (‰)
Gull ref.	D018	N/A	62°19'50"	78°09'16"	70	0.027	21 (2012)	23.0
Ocean spray ref.	D019	N/A	62°20'17"	78°09'30"	30	0.034	11 (2012)	10.6
Low	A036	Neta Islands	64°15'12"	76°18'21"	250	0.54	10 (1997)	5.42
	D007	North Skerries	62°26'43"	78°08'08"	50	0.040	8 (2012)	3.08
Mod.	A045	Tunitjuak Island	64°17'08"	75°46'56"	110	1.2	15 (2012)	7.14
	A054	Putaguk Island	64°19'04"	75°45'17"	100	0.096	243 (2012)	8.65
	A056	Qasigijjat	64°16'59"	75°44'25"	190	0.28	434 (2012)	6.30
	A114	Salunnaqtuuq	64°16'06"	74°11'20"	170	0.39	197 (2012)	9.64
	D003	North Skerries	62°25'52"	78°10'17"	130	0.24	228 (2012)	7.72
	D004	North Skerries	62°26'37"	78°09'02"	110	0.19	212 (2012)	7.68
	D012	South Skerries	62°23'01"	78°11'06"	70	0.11	230 (2012)	9.04
	D022	North Skerries	62°26'37"	78°09'02"	110	0.068	101 (2012)	9.82
High	A038	Neta Islands	64°14'51"	76°13'45"	50	0.010	7 (2011)	12.3
	A044	Simikutak	64°17'52"	75°47'14"	80	0.078	141 (2012)	12.2
	A083	Tatsiumajukallak	64°19'20"	74°40'01"	60	0.037	259 (2010)	11.6
	A085	Inugiavvik	64°17'32"	74°38'56"	180	0.17	225 (2010)	11.6
	A108	Qalirusilik	64°20'23"	74°22'33"	130	0.15	234 (2010)	12.2
	A135	Qujjautaq	64°03'44"	73°31'56"	170	0.25	127 (2012)	10.4
	A136	N/A	64°05'07"	73°30'44"	60	0.12	444 (2012)	13.6
	D013	South Skerries	62°22'56"	78°11'32"	50	0.058	74 (2012)	10.6
	D016	Île Pikiulik	62°19'20"	78°10'33"	60	0.054	367 (2012)	10.3

Table 2 Concentration and standard deviation (SD) of relevant elements in Common Eider (*n* = 2) guano.

Element	Concentration (µg/g dry weight ± SD)
As	2.15 ± 1.20
Ca	175 ± 7
Cd	0.17 ± 0.021
Cu	5.15 ± 0.49
P	980 ± 170
Pb	1.05 ± 0.07
Se	1.35 ± 0.071
Sr	770 ± 85
Zn	11.5 ± 0.7

Table 3 Water variables of the 21-pond set. Chlorophyll-*a* is expressed as CHL-*a*; dissolved inorganic carbon is expressed as DIC; dissolved organic carbon is expressed as DOC; total nitrogen filtered is expressed as TN-F; total phosphorus is expressed as TP, and is either filtered, -F, or unfiltered, -UF; conductivity is expressed as Cond. Mean and standard deviation are calculated with the gull colony, D018, and ocean spray pond, D019, omitted.

Influence	Lake	CHL-a (µg/L)	DIC (mg/L)	DOC (mg/L)	TN (mg/L)	TP-F (µg/L)	TP-UF (µg/L)	Cond. (µS/cm)	Ca^{2+} (mg/L)	K^{+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	SO_4^{2-} (mg/L)
Gull ref.	D018	429	14.8	47.1	7.90	3800	7100	1066	14.0	16.7	13.0	177	52.5
Ocean spray ref.	D019	8.00	10.1	14.2	1.17	30	93.0	13000	133	116	357	3350	862
Low	A036	18.5	8.60	10.2	0.867	65	101	172	8.95	2.14	2.36	17.3	5.80
	D007	20.1	10.2	19.8	2.36	34	103	5000	46.0	39.1	112	1060	328
	Mean ± SD	19.3 ± 1.13	9.40 ± 1.10	15.0 ± 6.8	1.61 ± 1.06	50 ± 22	102 ± 1.40	2590 ± 3410	28.0 ± 26.0	20.6 ± 26.1	57.2 ± 77.5	539 ± 737	167 ± 228
Moderate	A045	6.00	10.7	11.9	2.64	38	75.0	292	13.6	2.70	4.44	34.2	17.0
	A054	0.100	20.8	15.4	1.54	79	102	438	40.1	3.37	5.46	37.5	40.5
	A056	0.100	14.3	8.80	0.865	47	65.0	324	19.9	4.16	4.54	33.8	17.5
	A114	4.20	4.00	14.0	0.817	180	230	75.0	2.12	0.53	1.31	10.6	2.60
	D003	128	3.50	18.8	1.04	41	249	325	7.35	2.09	4.34	52.7	16.2
	D004	25.3	12.0	20.8	1.71	66	549	650	20.4	4.96	7.59	89.9	31.0
	D012	166	18.0	35.6	3.61	88	1260	1270	42.8	9.83	19.8	223	44.3
	D022	3.50	20.6	16.3	1.89	170	283	346	24.8	2.47	5.95	45.4	13.4
	Mean ± SD	41.7 ± 66.3	12.9 ± 6.80	17.7 ± 8.20	1.76 ± 0.962	89 ± 57	352 ± 399	465 ± 363	21.4 ± 14.4	3.76 ± 2.79	6.68 ± 5.59	65.9 ± 67.3	22.8 ± 14.3
High	A038	10.6	13.3	10.7	1.69	350	397	342	12.5	2.21	6.04	43.2	10.5
	A044	76.5	4.90	14.6	1.04	69	294	112	5.33	1.67	1.62	12.2	2.20
	A083	47.9	8.20	7.40	0.838	40	130	1490	17.7	9.08	25.0	209	54.6
	A085	3.60	9.30	17.9	1.46	510	594	157	12.1	0.94	2.18	16.8	3.70

	A108	3.10	9.90	13.5	1.39	230	308	332	9.21	2.50	5.64	43.6	13.4
	A135	33.8	9.20	14.8	1.38	71	304	117	10.1	0.51	1.70	12.0	4.00
	A136	14.2	9.60	14.7	1.44	49	161	198	12.1	0.84	3.70	17.5	12.9
	D013	7.20	10.6	21.6	2.57	52	126	414	27.2	3.66	6.34	60.3	21.9
	D016	1.20	26.6	40.2	24.0	1300	1430	750	32.0	5.80	8.85	85.9	31.3
	Mean ± SD	22.0 ± 25.8	11.3 ± 6.10	17.3 ± 9.50	3.98 ± 7.52	290 ± 401	416 ± 408	435 ± 445	15.4 ± 8.80	3.02 ± 2.81	6.79 ± 7.26	55.6 ± 62.8	17.2 ± 16.9

Table 3 continued

Influence	Lake	Al (µg/L)	As (µg/L)	Cd (µg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	Pb (µg/L)	Se (µg/L)	SiO_2 (mg/L)	Sr (µg/L)	V (µg/L)	Zn (µg/L)
Gull ref.	D018	52.3	8.45	0.199	0.34	5.22	196	0.165	1.6	1.6	189	3.3	17
Ocean spray ref.	D019	28.6	1.72	0.041	0.42	2.31	76.7	0.047	0.34	0.38	3180	2.0	1.7
Low	A036	36.5	0.24	0.009	0.22	9.34	91.3	0.171	0.07	0.39	27.5	0.68	1.3
	D007	19.8	2.02	0.053	0.15	6.32	114	0.083	0.30	0.72	833	1.3	2.1
	Mean ± SD	28.2 ± 11.8	1.13 ± 1.26	0.031 ± 0.031	0.19 ± 0.05	7.83 ± 2.14	103 ± 16.1	0.127 ± 0.062	0.19 ± 0.16	0.56 ± 0.23	430.3 ± 570.0	0.99 ± 0.44	1.7 ± 0.57
Moderate	A045	46.8	0.66	0.048	0.29	5.14	203	0.303	0.10	0.84	75.3	1.3	1.1
	A054	121	1.35	0.075	0.88	5.19	547	0.130	0.17	0.35	216	1.3	3.4
	A056	14.4	3.91	0.006	0.10	6.91	60.6	0.043	0.08	0.31	97.1	0.74	0.5
	A114	154	0.32	0.022	0.23	3.39	375	0.129	0.10	0.06	17.4	1.2	4.1
	D003	125	0.47	0.024	0.29	4.83	210	0.262	0.23	1.5	52.4	1.0	4.3
	D004	167	1.45	0.078	0.64	6.19	463	0.371	0.36	2.0	128	7.8	4.3
	D012	73.2	3.15	0.039	0.34	0.91	668	0.410	0.35	1.3	312	7.1	2.8
	D022	48.8	0.79	0.037	0.18	4.96	111	0.167	0.24	2.0	113	0.95	3.4
	Mean ± SD	93.8 ± 55.6	1.51 ± 1.32	0.041 ± 0.025	0.37 ± 0.26	4.69 ± 1.84	330 ± 218	0.227 ± 0.130	0.20 ± 0.11	1.1 ± 0.77	126 ± 95.2	2.7 ± 2.9	3.0 ± 1.5
High	A038	22.1	0.79	0.049	0.10	1.25	271	0.467	0.14	0.81	89.9	0.71	1.6
	A044	148	0.36	0.123	0.36	6.25	90.2	0.140	0.20	0.91	40.6	1.1	5.2
	A083	56.8	0.71	0.046	0.18	3.64	154	0.129	0.16	0.05	229	0.88	3.0
	A085	103	0.62	0.021	0.25	1.52	257	0.195	0.16	0.02	87.5	1.3	1.9
	A108	93.4	0.88	0.050	0.44	12.4	363	0.402	0.20	1.7	82.1	1.8	3.1
	A135	249	0.78	0.032	0.19	2.75	295	0.201	0.10	0.53	78.1	2.1	2.6
	A136	27.3	0.44	0.011	0.47	5.33	1370	0.026	0.10	0.14	75.5	0.57	1.5
	D013	49.6	1.02	0.038	0.35	2.79	275	0.601	0.38	0.13	171	6.2	2.1
	D016	94.7	4.34	0.056	0.31	3.53	1130	0.263	0.62	2.2	215	9.8	3.1
	Mean ± SD	93.8 ± 70.7	1.10 ± 1.23	0.047 ± 0.032	0.29 ± 0.12	4.38 ± 3.41	467 ± 455	0.269 ± 0.185	0.23 ± 0.19	0.72 ± 0.78	119 ± 68	2.7 ± 3.2	2.7 ± 1.1

Table 4 Sedimentary variables of the 21-pond set. Mean and standard deviation are calculated with the gull colony, D018, and ocean spray pond, D019, omitted. Bismuth and Sb were below detection for all sites and therefore omitted.

Influence	Lake	Ca^{2+} (mg/g)	K^{+} (mg/g)	Mg^{2+} (mg/g)	Na^{+} (mg/g)	P (mg/g)	Al (µg/g)	As (µg/g)	Ba (µg/g)	Be (µg/g)	Cd (µg/g)	Co (µg/g)	Cr (µg/g)	Cu (µg/g)
Gull ref.	D018	56	6.7	6.3	16	16	1400	6.9	37	0.03	0.86	2.8	7.2	10
Ocean spray ref.	D019	34	2.7	4.7	14	0.98	1800	0.9	37	0.03	0.09	3.2	16	5.7
Low	A036	15	3.8	3.1	2.6	3.7	1700	< 0.5	34	0.05	0.72	2.3	15	240
	D007	11	11	26	98	0.26	530	3.0	27	< 0.02	0.04	1.4	3.6	4.4
	Mean ± SD	13 ± 2.8	7.4 ± 5.1	15 ± 16	51 ± 67	2.0 ± 2.4	1100 ± 830	1.7 ± 1.7	31 ± 4.9	0.03 ± 0.02	0.38 ± 0.48	1.9 ± 0.63	9.3 ± 8.1	120 ± 170
Moderate	A045	8.5	4.5	3.8	0.75	5.6	2600	1.3	78	0.13	0.66	5.1	26	83
	A054	16	3.4	3.3	0.76	4.3	2300	1.6	150	0.05	2.5	8.7	21	91
	A056	16	3.8	4.6	0.97	3.0	3500	19	400	0.26	1.5	22	80	280
	A114	8.3	1.3	2.2	0.59	2.7	3700	0.8	62	0.16	4.1	10	25	130
	D003	29	2.7	4.4	1.7	2.4	4000	1.0	45	0.11	2.2	3.8	17	74
	D004	16	4.8	5.9	1.3	4.2	3600	2.2	94	0.06	1.0	4.9	22	66
	D012	14	3.8	3.0	2.3	4.8	710	5.7	18	0.03	1.6	1.8	12	20
	D022	60	4.6	5.7	1.2	4.7	3100	3.0	89	0.11	1.4	3.5	18	49
	Mean ± SD	21 ± 17	3.6 ± 1.2	4.1 ± 1.3	1.2 ± 0.57	4.0 ± 1.1	2900 ± 110	4.3 ± 6.1	120 ± 120	0.11 ± 0.07	1.9 ± 1.1	7.5 ± 6.5	28 ± 22	99 ± 80
High	A038	11	5.2	3.3	2.9	7.0	1100	0.8	9.0	0.04	1.8	0.90	5.9	13
	A044	16	2.1	9.6	0.61	3.3	14000	< 0.5	38	0.40	2.9	13	62	100
	A083	39	1.5	2.8	1.6	0.98	1900	< 0.5	38	0.05	0.28	2.2	14	6.1
	A085	12	3.1	1.6	0.37	4.5	690	0.7	9.2	0.03	3.3	1.4	7.7	25
	A108	8	2.9	4.0	1.2	2.0	2400	< 0.5	53	0.03	0.44	5.3	24	46
	A135	10	2.0	1.5	0.29	4.2	1100	2.0	7.5	0.04	3.4	1.7	7.4	45
	A136	13	2.9	2.6	2.0	5.6	2100	1.6	36	0.15	2.4	4.6	30	180
	D013	18	5.4	5.0	2.3	5.3	3300	2.7	47	0.09	0.84	3.2	12	16
	D016	12	2.0	2.3	0.96	3.1	1600	2.8	24	< 0.02	2.9	3.7	9.0	45
	Mean ± SD	15 ± 9.3	3.0 ± 1.4	3.6 ± 2.5	1.4 ± 0.91	4.0 ± 1.9	3100 ± 4200	1.3 ± 1.0	29 ± 17	0.09 ± 0.12	2.0 ± 1.2	4.0 ± 3.7	19 ± 18	53 ± 55

Table 4 continued

Influence	Lake	Fe (mg/g)	Li (µg/g)	Mo (µg/g)	Ni (µg/g)	Pb (µg/g)	Se (µg/g)	Sr (µg/g)	Ti (µg/g)	Th (µg/g)	U (µg/g)	V (µg/g)	Y (µg/g)	Zn (µg/g)
Gull ref.	D018	5.9	3	0.4	7.2	1.4	3.2	310	270	0.02	0.42	12	2.3	81
Ocean spray ref.	D019	17	4	0.8	5.9	0.88	0.7	190	400	0.05	0.25	48	5.9	20
Low	A036	4.7	3	2	13	12	1.4	53	180	0.17	11	13	4.1	55
	D007	1.4	5	0.3	5.3	0.60	< 0.7	190	150	< 0.02	0.12	4.0	0.54	10
	Mean ± SD	3.1 ± 2.3	4 ± 1	1 ± 1	9.2 ± 5.4	6.3 ± 8.1	0.95 ± 0.49	120 ± 97	170 ± 21	0.10 ± 0.11	5.6 ± 7.7	8.5 ± 6.4	2.3 ± 2.5	33 ± 32
Moderate	A045	8.7	6	0.8	40	12	1.3	49	480	0.11	0.9	18	3	53
	A054	9.3	8	0.3	86	2.4	1.5	93	320	0.13	0.21	14	1.3	70
	A056	12	28	1	250	10	2.8	170	1230	0.3	1.9	51	3.4	120
	A114	8.1	3	1	56	16	5.3	160	260	0.07	2.3	23	15	330
	D003	9	4	0.3	54	12	3.5	150	360	0.09	3.8	12	7.9	130
	D004	13	5	0.3	15	5.1	2.4	84	680	0.12	1.1	25	5.9	68
	D012	5.8	< 2	< 0.1	8.2	5.0	2.9	90	130	0.04	0.21	13	1.3	75
	D022	9.2	6	0.3	13	4.1	3.2	230	470	0.1	0.66	19	5.4	72
	Mean ± SD	9.4 ± 2.2	7.8 ± 8.4	0.5 ± 0.4	65 ± 79	8.3 ± 4.8	2.9 ± 1.3	130 ± 59	490 ± 340	0.12 ± 0.08	1.4 ± 1.2	22 ± 13	5.4 ± 4.5	110 ± 91
High	A038	4.3	3	0.4	3.2	9.2	1.3	85	180	0.05	1.0	6.0	1.5	62
	A044	17	35	0.2	29	7.3	2.1	130	840	0.11	0.53	105	4.7	140
	A083	8.7	5	0.6	5.9	1.2	< 0.7	250	360	0.07	0.35	16	7.2	26
	A085	3.1	< 2	0.4	8.7	4	2.3	92	64	0.04	0.39	4.0	1.2	120
	A108	16	4	0.4	15	3.4	< 0.7	49	630	0.09	0.61	33	5.1	44
	A135	2.5	< 2	0.4	20	2.8	< 0.7	62	93	< 0.02	3.0	5.0	2.5	120
	A136	31	< 2	0.5	48	3.8	2.5	92	150	0.07	0.60	19	4.8	130
	D013	13	4	0.6	6	10	2.4	88	550	0.08	0.73	31	6.0	70
	D016	4.3	< 2	0.4	11	2.6	3.2	76	300	0.05	0.39	13	1.7	150
	Mean ± SD	11 ± 9.3	7 ± 11	0.4 ± 0.1	16 ± 14	4.9 ± 3.1	1.8 ± 0.93	102 ± 60	350 ± 270	0.06 ± 0.03	0.84 ± 0.83	26 ± 32	3.9 ± 2.2	96 ± 46

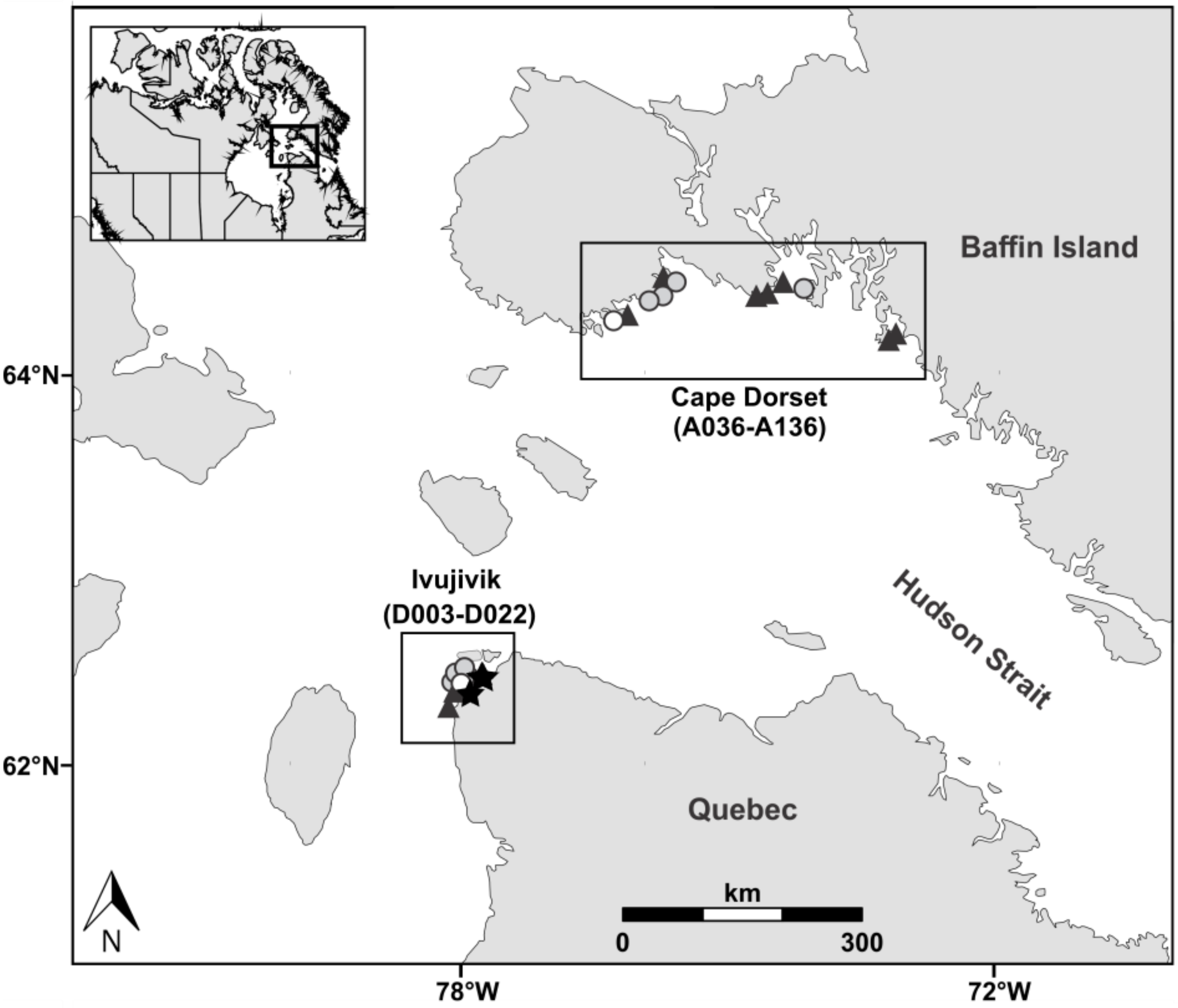

Fig. 1 Map showing the locations of the study ponds. Reference ponds are represented by black stars; low influence ponds (active nests ≤ 10; $\delta^{15}N \leq 6‰$) are represented by open circles; moderate influence ponds ($\delta^{15}N <$ 10‰) are represented by grey circles; high influence ponds ($\delta^{15}N > 10‰$) are represented by black triangles.

Fig. 2 On the left is an image of a low-influence pond, A036, with minimal vegetation, and on the right, is a high-influence pond, D016, with lush vegetation.

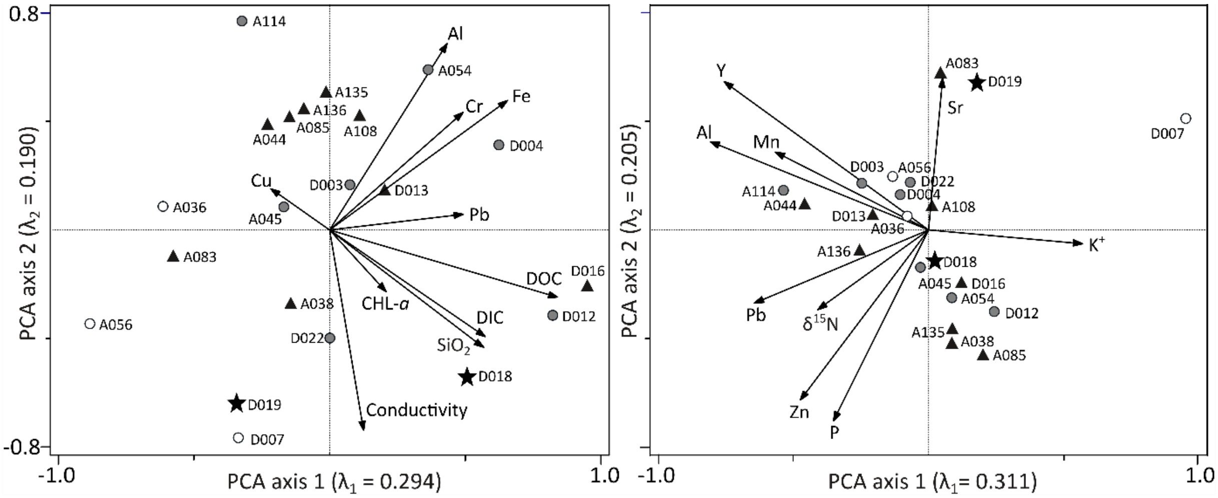

Fig. 3 Principal components analysis (PCA) of the 21-pond set. On the left is a PCA of water variables; on the right is a PCA of sedimentary variables. Reference ponds are represented by black stars; low influence ponds (active nests ≤ 10; δ^{15}N ≤ 6‰) are represented by open circles; moderate influence ponds (δ^{15}N < 10‰) are represented by grey circles; high influence ponds (δ^{15}N > 10‰) are represented by black triangles. Dissolved organic carbon is expressed as DOC; dissolved inorganic carbon is expressed as DIC; chlorophyll-*a* is expressed as CHL-*a*.