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An isotopic investigation of mercury accumulation in terrestrial food webs adjacent to an Arctic seabird colony

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ABSTRACT

At Cape Vera (Devon Island, Nunavut, Canada), a seabird colony of northern fulmars (*Fulmarus glacialis*) congregates and releases nutrients through the deposition of guano to the coastal terrestrial environment, thus creating nutrient-fertilized habitats important to insects, birds, and mammals. Here we determined whether mercury was similarly enriched in various terrestrial food web components in this High Arctic coastal ecosystem due to seabird inputs. Stable isotopes (δ^{15}N, δ^{13}C) were used to identify trophic linkages and possible routes of contaminant transfer in the food web. Values of δ^{15}N were significantly higher in lichens and certain plants collected closer to the bird colony, demonstrating a gradient of seabird influence, and were higher at Cape Vera than our reference site at Cape Herschel, on eastern Ellesmere Island, an area relatively unaffected by seabirds. In contrast, δ^{13}C showed little variation among terrestrial species, suggesting minimal influence by seabirds. Concentrations of total mercury (THg) in primary producers and phyto/zooplankton were not significantly correlated with distance from the seabird colony or δ^{15}N values, and were similar to other taxa from the High Arctic. Our results provide novel data on THg in several Arctic taxa where concentrations have not been reported previously. Moreover, the analyses indicate that δ^{15}N is significantly enriched in the adjacent environment by guano fertilization, but our study was unable to show an enrichment of THg and δ^{13}C in the terrestrial food web near the seabird colony.

1. Introduction

For long range transport, atmospheric and ocean currents are the major transfer routes of many contaminants such as mercury to the Arctic (Gamberg et al., 2005). However, recent studies have demonstrated that biovector transport, the ability of migratory species to focus and release nutrients and contaminants at specific receptor sites, may have important consequences to the Arctic (Blais et al., 2007). For example, contaminants can be efficiently transferred to coastal and inland freshwater ecosystems via migratory birds and fish (Ewald et al., 1998; Krümmel et al., 2003; Evenset et al., 2004; Gregory-Eaves et al., 2007). This form of contaminant transport may be particularly significant in the Arctic, Antarctic, and other areas where many bird, fish, and mammal species congregate as seasonal migrants.

In the Canadian Arctic, millions of seabirds return to a few breeding colonies each year (Mallory and Fontaine, 2004), and focus nutrients and contaminants at these sites through deposition of guano, dropped prey, and mortality (Cocks et al., 1998). One such site is Cape Vera, Devon Island, Nunavut (Fig. 1), where northern fulmars (*Fulmarus glacialis*) serve as keystone species by supporting a rich and diverse ecosystem below the cliffs of their colony (Blais et al., 2005).

Several studies have found elevated concentrations of heavy metals and stable isotopes in terrestrial and marine primary producers adjacent to seabird cliffs relative to those farther away from the colony (Godzik, 1991; Headley, 1996; Wainwright et al., 1998). Evidence for nutrient enrichment of ponds at Cape Vera by seabirds has been quantified by algal growth, nutrients such as total nitrogen (TN) and total phosphorus (TP), and nitrogen stable isotopes (Blais et al., 2005; Keatley et al., 2009). The landscape immediately adjacent to the seabird cliffs of Cape Vera is blanketed by mosses (e.g., *Bryum* spp., *Drepanocladus* spp.), saxifrage (*Saxifraga* spp.), and lichens (e.g., *Xanthoria*); however, areas outside of seabird influence at Cape Vera are a polar desert, almost devoid of vegetation (Blais et al., 2007).

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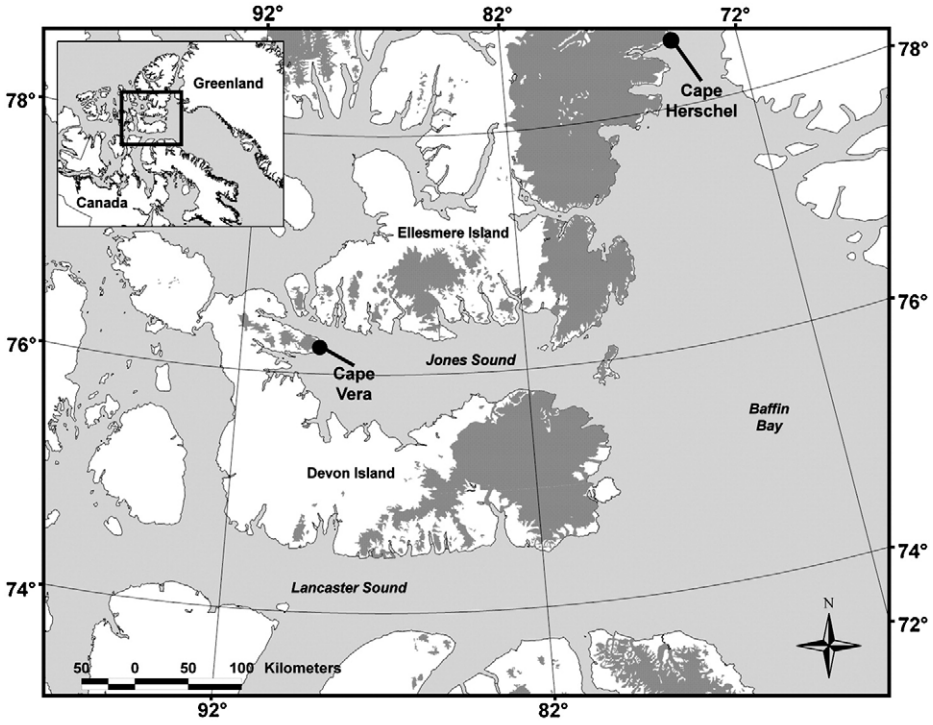

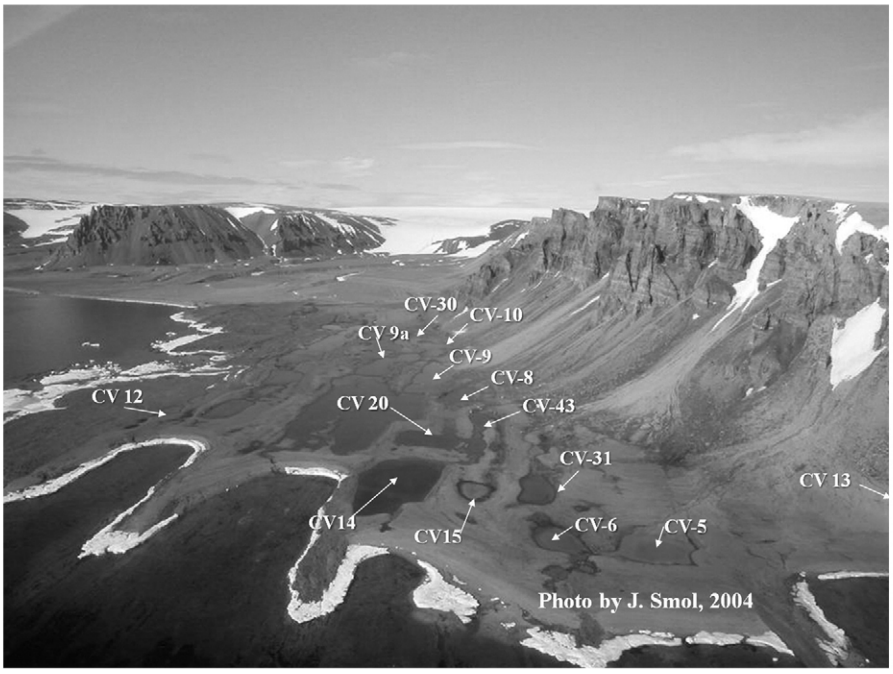

Fig. 1. Main study site at Cape Vera, Devon Island, Nunavut (76°15′N, 89°15′W) and our reference site at Cape Herschel, Ellesmere Island, Nunavut (78°37′N, 74°42′W (Douglas and Smol) 1994). Arrows and labels indicate ponds where samples were collected at the base of the seabird cliffs.

The purpose of this study was to determine if organisms living below the fulmar colony had elevated THg concentrations relative to reference sites due to subsidies from fulmar guano. To accomplish this, we predicted that values of stable isotopes of nitrogen (δ^{15}N) and carbon (δ^{13}C) would be enriched in primary producers and animals near the seabird colony. We examined if THg concentrations in food webs at Cape Vera were influenced by seabird guano, and in particular if distance from the seabird colony influenced THg levels in biota. Although data are scarce, THg concentrations in terrestrial High Arctic species are generally low (AMAP, 1998; Poissant et al., 2008), but may become enriched from biovector transport (Blais et al., 2005, 2007). We analyzed THg concentrations in primary producers and phyto/zooplankton across a range of distances from the seabird colony, as well as at a distant reference site (Cape Herschel on Ellesmere Island).

2. Methods

2.1. Study area

Cape Vera is located on Devon Island, Nunavut (Fig. 1; 76°15′N, 89°15′W). Cliffs extend 6.4 km along the coastline of Cape Vera and are approximately 300 m above sea level (Gaston et al., 2006). We sampled a series of 12 sites adjacent to ponds (CV# 5, 6, 8, 9, 9a, 10,

13–15, 20, 30, and 31) located below the seabird cliffs with distances between ponds and the cliffs spanning 4 km (Blais et al., 2005).

Samples of lichen and saxifrage were collected at different elevations and from rocky ledges at the base of the cliff. Jewel lichen (*Xanthoria elegans*) was collected on the cliffs at elevations of 119 and 140 m above sea level. Worm lichen (*Thamnolia vermicularis*) was collected on the cliffs at 65 m. Saxifrage and lichen samples were also collected along a rocky ledge 6 m high at the base of the cliff, next to CV43 approximately 34 m from the main cliff of the colony.

Reference (background) ponds (CV 1, 12, and 40) were located approximately 2.5 to 4 km away from the immediate influence of the seabird colony (Fig. 1) and were chosen based on their distance from the colony. Lichen, saxifrage, periphyton, and zooplankton samples were also collected from three ponds (Pond 12, Willow and Horseshoe ponds) at Cape Herschel on Ellesmere Island (78°37′N, 74°42′W; Fig. 1), an area without seabirds that has been the subject of extensive long-term limnological and paleolimnological research (Smol and Douglas, 2007a,b). Douglas and Smol (1994) provide a map of Cape Herschel, including descriptions of these three study sites.

2.2. Sample collection and preparation

All food web samples (Fig. 2) were collected from or near the ponds from 1 to 20 July 2006, and from 8 to 21 July 2007. Lichens, whole flowers (purple saxifrage, *Saxifraga oppositifolia*; tufted saxifrage, *S. caespitosa*), and fungi were collected in 50 mL falcon tubes that were pre-rinsed with acetone and hexane, or in sterile Whirlpaks®. Three falcon tubes of each lichen species and two tubes of flowers were collected near the 13 ponds in 2006. In 2007, lichen and plant samples were taken from varying altitudes along the seabird cliff and at control sites CV1 and Cape Herschel on Ellesmere Island. *X. elegans* was scraped off of flat rocks using field knives that were wiped clean and dry between pond sites. *T. vermicularis* was collected using stub-ended large tweezers. Samples were put on sea ice in a cooler for approximately 2–3 weeks until they were transferred to the freezer room at the Polar Continental Shelf Program (PCSP) base at Resolute Bay, Nunavut, and were then shipped to the laboratory in Ottawa, Ontario. Saxifrage and lichen samples were weighed and freeze-dried for 48 h, then homogenized using a Magic Bullet® blender in preparation for THg, δ^{15}N and δ^{13}C analyses. The blender blade and plastic bowl were cleaned and rinsed with distilled water and ethanol, then dried completely between samples.

From each pond, periphyton, mixed samples of zooplankton and phytoplankton, and chironomids were collected. Periphyton samples were collected in 2007 from rocks in 13 ponds at Cape Vera and two from Cape Herschel. Before sampling, GF/F 47 mm filters were ashed in a muffle furnace at 500 °C for 5 h and sealed in Petri dishes. Rocks were collected along the shoreline of each pond in water 0.01 to 0.5 m deep, and were scrubbed on site vigorously in a 23×23 cm steel-coated baking pan filled with 250 mL of pond water using a nail brush specific to each pond. Surface areas of the periphyton were determined by wrapping the rocks with tinfoil and using the surface area to mass ratio calculated for the foil. The periphyton mixture was then filtered through a GF/F 47 mm filter using an electric pump. The filters were placed in a Petri dish and sealed in a Whirl-Pak® bag. Samples were placed on sea ice in a cooler until they were transferred to the freezer room at PCSP. At the University of Ottawa, Petri dishes and the aluminum foil were weighed in order to determine periphyton mass and surface area. Samples were freeze-dried for 48 h, scraped from filters, and homogenized using a clay mortar and pestle.

Zooplankton and phytoplankton samples were collected by horizontal hauls at depths of approximately 1 m using a plankton net (mesh size 61 μm) and placed in 50 mL falcon tubes that were pre-rinsed with acetone and hexane. Three falcon tubes were collected from each pond at Cape Vera ($n=13$) and Cape Herschel in 2006. Chironomid samples were collected from 2005 to 2007 from 11 ponds at Cape Vera using emergence (designed by J. R. Glew, Queen's University) and malaise traps (Townes, 1972) as well as an aerial insect net. The malaise trap was placed by the edge of a pond, entrapping newly emerged adult chironomids. The aerial insect net was used to catch adult chironomid swarms at a pond. Upon collection, both chironomid and zooplankton samples were put on sea ice in a cooler for approximately 2–3 weeks until they were transferred to PSCP, and then were frozen and shipped to the University of Ottawa. Sample identification was conducted using a dissection microscope, and a subset of each sample was preserved in alcohol.

Several small animals were collected from Cape Vera. Fifty Victor® snap traps were set in 2006 and 2007 beside burrows of *Dicrostonyx groenlandicus*, the northern collared lemming, and checked every morning and evening. Weight and sex of all lemmings were recorded.

We captured 25 snow buntings (*Plectrophenax nivalis*), 11 in 2006 and 14 in 2007, in Victor® traps or by shooting with a 12 gauge shot gun using steel pellets. All buntings were sexed and sealed in Ziploc® plastic freezer bags. In 2007, five buntings were captured from CV1 as controls. In 2007, two ermine (*Mustela erminea arctica*) were captured. We took GPS

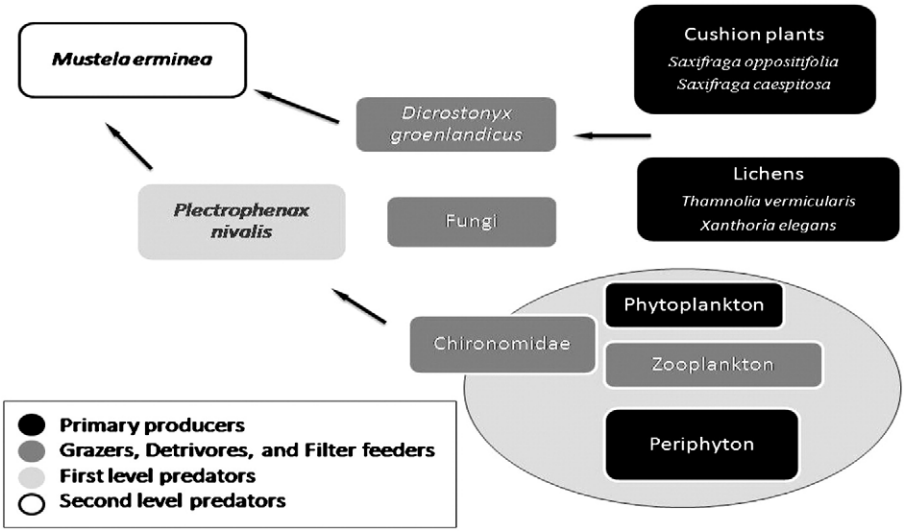

Fig. 2. Trophic linkages among organisms collected from the coastal ecosystem at Cape Vera, Devon Island, Nunavut, Canada. Trophic linkages are represented by arrows and are supported by stomach content analysis and literature (Krebs et al., 2003; Falconer et al., 2008). The oval represents the ponds at Cape Vera and encompasses the organisms that inhabit it.

coordinates at all capture sites, and put carcasses on sea ice in a cooler for approximately 2–3 weeks until they were transferred to freezers at PCSP.

At the University of Ottawa, animal samples were dissected and prepared for THg and isotope analysis. To verify trophic linkages within our food web, stomach content identifications were performed on all animals. Mammals were weighed, sexed, and skinned: the gastrointestinal tract was removed for stomach content analysis. Birds were weighed, and plucked of feathers; the gastrointestinal tract was removed for stomach content analysis. Animal samples were homogenized using liquid nitrogen in the M20 IKA Works® Universal Mill. After homogenization, 1–2 g subsamples were placed in microcentrifuge tubes for THg and stable isotope analysis. The mill was cleaned with distilled water and ethanol and dried in between samples. All samples were freeze-dried for 72 h and re-homogenized.

2.3. Stable isotope analyses

Freeze-dried whole body tissue was used for stable isotope analyses after running a preliminary test between different tissues which showed the stable isotope values for liver to be the same as for whole body. Samples were analyzed for $\delta^{13}C$ and $\delta^{15}N$ at the G.G. Hatch Isotope Lab at the University of Ottawa using well-established and standard procedures (Peterson and Fry, 1987). Samples were flash combusted at 1800 °C in an elemental analyser (EA) (EA 1110, CE Instruments, Italy) coupled to a stable isotope mass spectrometer (DeltaPlus Advantage IRMS, ThermoFinnigan, Germany) with a Conflo interface (Conflo III). Carbon and nitrogen stable isotope values were calculated relative to Pee Dee belemnite (PDB) and atmospheric nitrogen (N_2) normalized to internal standards calibrated to international standards with an analytical precision of ±0.2‰. Triplicate assays were run every sixth sample.

A subset of carbon isotope samples for lichen, saxifrage, periphyton, and zooplankton was pretreated for carbonates via acid fumigation to make sure that the carbonates of rocks, sediment, and carapaces did not interfere with the isotope values of the organisms. Samples were moistened using high-performance liquid chromatography-grade water and placed in a sealed vessel with an open beaker of HCl for 48 h. The samples were freeze-dried, re-homogenized, and weighed for isotope analysis. Slight and insignificant differences were observed between carbonate-treated and untreated samples, and only treated samples were used for further analyses.

2.4. THg analysis

Freeze-dried whole body tissue was analyzed for THg concentrations at the University of Ottawa using a Nippon Hg Analyser SP-3D (Nippon Instruments Corporation, Osaka, Japan) with a detection limit of 0.01 ng/sample. Each sample was analyzed with 0.1 M NaOH buffer, calcium hydroxide [$Ca(OH)_2$], activated alumina (Al_2O_3), and 1:1 sodium carbonate (Na_2CO_3) as additive agents. Approximately 10 to 20 mg of lichen, saxifrage, periphyton, fungi, zooplankton, and stomach contents, and approximately 5 to 10 mg of chironomid, lemming, bunting, and ermine tissues were analyzed.

All steel utensils used for dissections (weighing implements, scissors, tweezers, and scalpels) were rinsed with distilled water and American Chemical Society (ACS) grade acetone and hexane before being heated at 200 °C in a glassware oven for 12 h prior to use. Following every fifth sample, blanks and standards were run for quality control. The average recovery for standards from stock Mercury Reference Standard Solution [certified 1000 ± 10 µg/g (SD); Fisher Scientific, CSM114-100] was 95.3 ± 0.09% (SD, $n = 60$). Every sixth sample was run in triplicate. Mean coefficients of variation for triplicate samples were low (i.e., similar values), and ranged between 1.9 and 6.3%.

Three replicates of DORM-3 certified reference material (0.382 ± 0.06 mg/kg; National Research Council of Canada, Ottawa, ON) were run with triplicates of each sample type (buntings, ermine, and lemmings). The mean recovery of DORM-3 was 0.363 mg/kg (95%, $n = 3$) with a CV of 1.6%.

2.5. Statistical analyses

All data were analyzed using Systat® 12 and SigmaPlot® 10 (Systat Software, Point Richmond, CA, USA). Linear regressions were created using SigmaPlot. One-way analyses of variance (ANOVAs) were performed using Systat®12, and were followed by Tukey HSD pairwise comparisons. Distances were measured between the Cape Vera ponds and the most productive pond at the base of the cliffs (CV 8) as in Brimble et al. (2009). Cape Herschel was not included in the analyses involving distance.

3. Results and discussion

3.1. Stable isotopes and food web structure

At Cape Vera, organisms of freshwater origin (chironomids, zooplankton, and periphyton) had significantly higher $\delta^{13}C$ values than

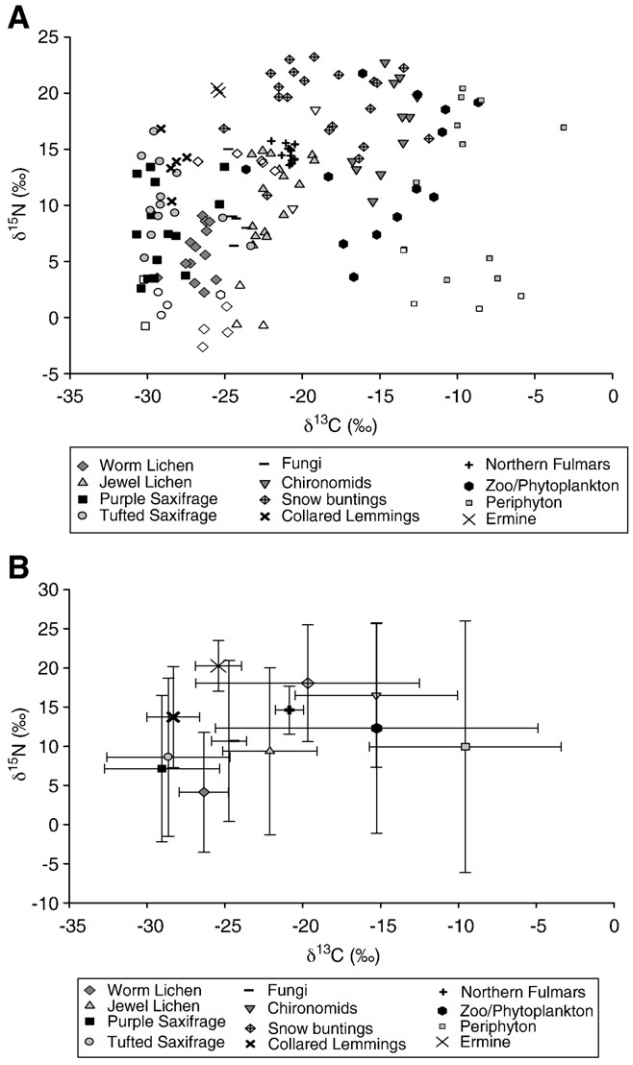

Fig. 3. A. Carbon and nitrogen isotope values of several species from Cape Vera, Devon Island, and Cape Herschel, Ellesmere Island, from 2005 to 2007 ($n = 180$). Open symbols represent samples from Cape Herschel. B. The mean carbon and nitrogen isotope values of several species from Cape Vera, Devon Island, and Cape Herschel, Ellesmere Island from 2005 to 2007 ($n = 180$). Error bars represent the 95% confidence limits. Northern fulmar data are representative of the marine food web and were provided by Karen Foster (personal communication).

Table 1
Total mercury concentrations [ng/g dw] and carbon and nitrogen isotope values of species and their stomach contents collected from Cape Vera.

Sample	Pond	δ^{15}N (‰)	δ^{13}C (‰)	THg	Stomach contents	δ^{15}N (‰)	δ^{13}C (‰)	THg
Bunting	CV1	13.9	−26.3	69.4	80% seeds	7.16	−24.3	N/A
Bunting	CV7	21.1	−19.7	100	60% sand/ sediments	14.5	−9.59	16.5
					15% seeds	14.1	−22.2	N/A
Bunting	CV8	19.7	−21.5	272	85% sand	18.6	−6.93	13.4
					15% chironomids	15.5	−23.7	N/A
Bunting	Edge of CV8	16.8	−25.1	116	40% chironomids	18.9	−24.0	N/A
Bunting	Near stream	10.9	−22.3	570	50% chironomids	5.62	−19.9	175
Bunting	CV1	13.1	−21.8	307	30% chironomids	13.1	−19.7	56.8
Bunting	CV10	23.0	−20.8	425	70% chironomids	20.9	−15.9	188
Bunting	CV10	22.2	−13.5	80.8	70% chironomids	19.8	−13.9	86.2
Bunting	CV10	21.0	−15.4	79.9	35% sand/plant material	19.2	−9.67	16.9
Bunting	CV10	21.6	−17.7	86.0	95% chironomids	18.3	−19.3	42.0
Bunting	CV12	15.2	−16.0	57.7	75% chironomids	13.9	−14.8	41.4
Bunting	CV7	20.9	−15.2	84.2	70% chironomids	17.5	−11.3	36.2
Bunting	CV7	16.7	−18.3	106	40% chironomids	13.3	−20.1	66.0
Bunting	CV8	23.2	−19.2	306	25% chironomids	18.7	−19.2	N/A
Bunting	CV8	17.0	−18.1	92.3	80% chironomids	16.9	−22.7	53.4
Lemming	near CV10	13.3	−28.5	32.1	100% moss	12.5	−28.8	130
Lemming	CV8	13.9	−28.1	65.7	100% moss	12.6	−28.9	81.7
Lemming	CV9	14.3	−27.4	24.1	100% moss	13.6	−29.0	110
Lemming	CV7	10.4	−28.4	10.3	100% moss	9.8	−28.9	132
Lemming	CV8	16.8	−29.2	348	100% moss	15.0	−29.1	57.2
Ermine	CV8	20.4	−25.5	231	50% feathers	19.2	−19.3	320
					50% bunting tissue	20.1	−20.1	203

organisms of terrestrial origin (lemmings, saxifrage, lichen, ermine, and fungi; ANOVA, $F_{11,137}=80.7$, $p<0.0001$; Tukey HSD pairwise comparisons, $p<0.05$). Zooplankton and chironomids had similar δ^{13}C values that differed from the other taxa ($p<0.05$, Tukey HSD). Periphyton δ^{13}C values were significantly higher than all other taxa ($p<0.05$, Tukey HSD). There was a greater variation in δ^{13}C values among freshwater species than terrestrial species (Fig. 3). δ^{15}N values differed significantly among organisms (ANOVA, $F_{11,137}=12.8$, $p<0.0001$) but were likely influenced by trophic status, with δ^{15}N values in ermine, snow buntings and chironomids significantly higher than values in primary producers.

The trophic linkages that we established using stable isotope results were consistent with trophic relationships discussed in the literature (Krebs et al., 2003). For example, the contents of one ermine stomach consisted of feathers and bones, probably a young snow bunting as the ermine was observed hunting a nest before being harvested (Table 1). Ermine prey primarily on lemmings (Gilg et al., 2006), although they will hunt buntings. We found no differences between the δ^{13}C values of ermine, lemmings and buntings ($p>0.05$). Stomach contents of collared lemmings were well-digested and difficult to identify, but appeared to be principally moss/plant material (Table 1). Correspondingly, the low δ^{13}C values of collared lemmings (Table 2) were similar to the low values of moss (Table 1), suggesting that they feed from the terrestrial ecosystem (Figs. 2 and 3).

The majority of snow bunting stomachs at Cape Vera contained small rocks, seeds, and the remains of macroinvertebrates, which were likely chironomids (Falconer et al., 2008). The range of δ^{15}N values for bunting stomach contents was from 5.6 to 20.9‰ and from −9.6 to −24.3‰ for δ^{13}C (Table 2). Snow buntings collected near reference site CV1 had significantly lower δ^{15}N values (t-test, $t_{23}=-3.46$, $p=0.002$) and δ^{13}C values ($t_{23}=-3.28$, $p=0.003$) than those from the ponds close to the fulmar colony at Cape Vera. There were no significant differences in δ^{15}N values among age classes of snow buntings, but hatch-year buntings had significantly higher δ^{13}C values than adults (ANOVA, $F_2=5.38$, $p=0.01$).

3.2. Stable isotopes as indicators of seabird-derived nutrients

Nitrogen in seabird guano has undergone several trophic transfers in the marine food web and has enriched δ^{15}N signatures compared to baseline primary producers that acquire this N source (Evenset et al., 2007). In our assessment of the effect of distance from the seabird colony on δ^{15}N, we found that primary producers collected farther from the seabird colony had lower δ^{15}N (Fig. 3B). Among primary producers, δ^{15}N in jewel lichen (Fig 4A; $R^2_{16}=0.35$, $p=0.02$), worm lichen (Fig. 4B; $R^2_{16}=0.38$, $p=0.02$), and tufted saxifrage (Fig. 4C; $R^2_{14}=0.37$, $p=0.02$) increased significantly for samples collected closer to the seabird colony. Purple saxifrage, periphyton and zooplankton showed similar trends between δ^{15}N and proximity to the colony, but the relationships were not statistically significant (Fig. 4). That all six taxa showed the same pattern is unlikely to occur by chance (Binomial test, $p=0.016$).

As an additional analysis, we compared the δ^{15}N values of organisms to the δ^{15}N values of sediment from adjacent ponds. Sediment δ^{15}N data were provided by Brimble et al. (2009), and were not available for every pond. In particular, the δ^{15}N values of primary producers, phyto/zooplankton and chironomids were significantly related to δ^{15}N values in pond sediment (Fig. 5; $R^2=0.37$, $p<0.0001$). The δ^{15}N values in pond sediment were also inversely related to distance from the seabird cliffs ($R^2=0.30$, $p=0.04$).

Within primary producers, relationships between δ^{13}C and δ^{15}N values did not indicate a strong gradient of seabird influence. Jewel lichen (Table 2, Fig. 6A; $R^2_{18}=0.36$, $p=0.01$) and zooplankton (Table 2, Fig. 6F; $R^2_{14}=0.29$, $p=0.046$) that had higher δ^{15}N also had higher δ^{13}C, but relationships for the other taxa were not significant. Since δ^{13}C varied little outside of the aquatic environment and showed no

Table 2
Carbon and nitrogen isotope values of several taxa from Cape Vera, Devon Island, Nunavut and Cape Herschel, Ellesmere Island from 2005 id="ins8" orig="–"; to 2007 ($n=147$). Correlation analysis was performed between δ^{15}N and δ^{13}C values and * indicates significance.

Species	δ^{15}N (‰)		δ^{13}C (‰)		r^2	p	N
	Mean ± SE	Range	Mean ± SE	Range			
Worm lichen	4.14 ± 0.88	−2.62–9.07	−26.3 ± 0.18	−27.5–(−24.8)	0.12	0.18	17
Jewel lichen	9.37 ± 1.19	−0.62–14.9	−22.1 ± 0.34	−24.2–(−19.2)	0.36	0.01*	18
Purple saxifrage	7.14 ± 1.10	−0.76–13.4	−29.0 ± 1.74	−30.7–(−25.0)	0.11	0.20	16
Tufted saxifrage	8.60 ± 1.19	0.17–16.6	−28.6 ± 0.47	−30.3–(−23.3)	0.02	0.63	16
Fungi	10.7 ± 1.71	6.4–16.8	−24.7 ± 0.19	−25.1–(−23.9)	0.53	0.10	6
Periphyton	9.94 ± 1.94	0.79–20.4	−9.56 ± 0.74	−13.5–(−3.13)	0.03	0.57	15
Phyto/zooplankton	12.3 ± 1.66	2.03–21.8	−15.3 ± 1.28	−25.3–(−8.65)	0.29	0.05*	14
Chironomids	16.5 ± 1.18	9.71–22.7	−15.3 ± 0.67	−20.6–(−13.1)	0.29	0.06	13
Collared lemming	13.7 ± 1.04	10.4–16.8	−28.3 ± 0.27	−29.1–(−27.4)	0.08	0.65	5
Snow bunting	18.1 ± 0.73	10.9–23.2	−19.7 ± 0.70	−26.7–(−13.5)	0.04	0.31	25
Ermines	20.3 ± 0.18	20.1–20.4	−25.4 ± 0.08	−25.5–(−25.3)	N/A	N/A	2

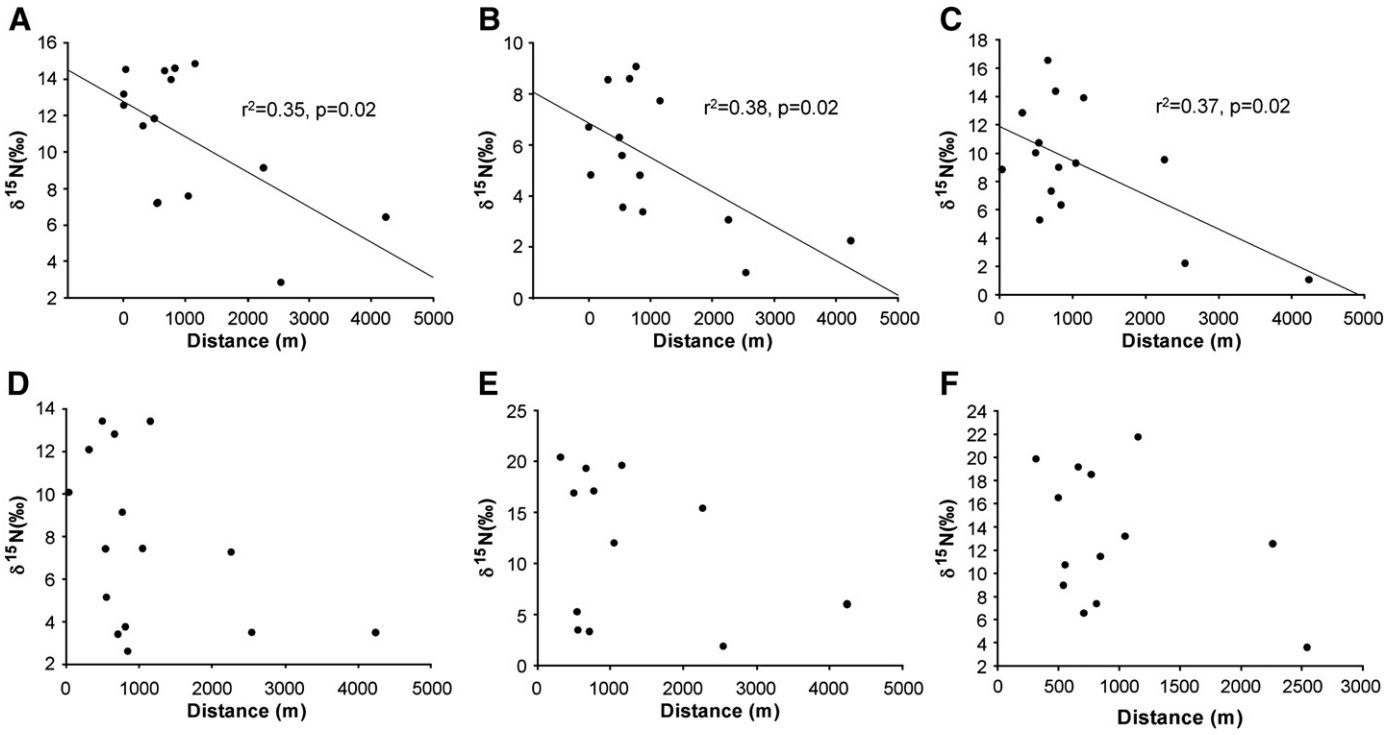

Fig. 4. The relationship between distance from the cliffs and δ^{15}N values for A) jewel lichen B) worm lichen C) tufted saxifrage D) purple saxifrage E) periphyton ;and F) zooplankton from Cape Vera r^2 and p values are only reported for significant relationships.

relationship to δ^{15}N, δ^{13}C is probably not a good indicator of seabird influence for terrestrial ecosystems. Similarly, Cocks et al. (1998) found little variation in δ^{13}C among terrestrial primary producers and soil samples collected from nunataks with and without seabirds.

In our comparisons, δ^{15}N values of the same taxa differed markedly. Jewel lichen ($t_{4.3} = -3.87$, $p = 0.02$), worm lichen ($t_{11} = -8.39$, $p < 0.001$), and periphyton ($t_{12.3} = -5.19$, $p < 0.001$) from Cape Vera had significantly higher δ^{15}N values than those found in the same species collected at Cape Herschel. Although highly variable, δ^{13}C values from species at Cape Vera were not significantly different from those species at Cape Herschel (all $p > 0.05$; Table 3).

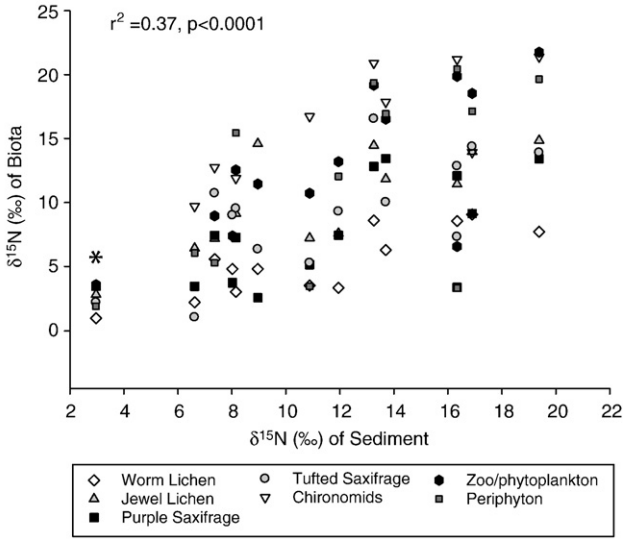

Fig. 5. The relationship between the δ^{15}N values of organisms and the sediment from the ponds they were collected from or near at Cape Vera. Sediment δ^{15}N values were provided by Brimble et al. (2009). * Indicates samples collected near reference pond CV 1.

In comparison to other Arctic Canadian studies, δ^{15}N and δ^{13}C values for periphyton and zooplankton from Cape Vera were elevated. For example, in lakes on the Mackenzie Delta, periphyton δ^{15}N (2.39 to 4.03‰, $n = 4$) was up to five times lower and δ^{13}C values (−27.66 to −30.10‰, $n = 4$) three times lower than at Cape Vera (Hecky and Hesslein, 1995). In the same study, maximum δ^{15}N (6.14‰) in zooplankton was twice as low and 9‰ lower for δ^{13}C than the average values of zooplankton from ponds at Cape Vera (Hecky and Hesslein, 1995). Collared lemmings at our site had markedly higher mean δ^{15}N values (13.73 ± 1.04‰) than lemmings at Karrak Lake, central Nunavut (4.3 ± 0.8‰, $n = 8$; Welch's $t_6 = 17.3$, $p < 0.001$) (Samelius et al., 2007), and lemmings collected on Bylot Island (1.42‰, $n = 18$) (Giroux, 2007; Tarroux, 2008). There was little variation in δ^{13}C values among collared lemmings. Although organisms from Cape Vera have elevated isotopic values, there could be other factors that influence stable isotopes in different systems. Benthic and planktonic algae have different δ^{13}C values which affect the isotopic composition of the food web supported by these carbon sources (France, 1995).

3.3. THg concentrations and food web structure

Jewel lichen and fungi had the highest mean concentrations of THg at Cape Vera (Table 4). Lichens lack an external root system and absorb most of their nutrients from the atmosphere, and thus are commonly used to monitor spatial and temporal patterns of contaminant concentrations (Nash and Gries, 1995; Poissant et al., 2008). Snowmelt may also be a significant source of contaminants to lichen (Ford et al., 1995). Moreover, because lichens are long-lived, they can accumulate Hg over many years (I. Brodo, pers. comm.). Soil contamination is the main source of Hg to mushrooms and fungi, which are also effective indicators of local contamination. However, similar to lichen, the ability of fungi to act as contaminant bioindicators varies by species (Falandysz et al., 2003).

Ermine and snow buntings had the next highest concentrations in THg (Table 4). However, with a range from 45.9 to 569.5 ng/g (dw), 30% of the buntings from Cape Vera surpassed the mean THg concentration of

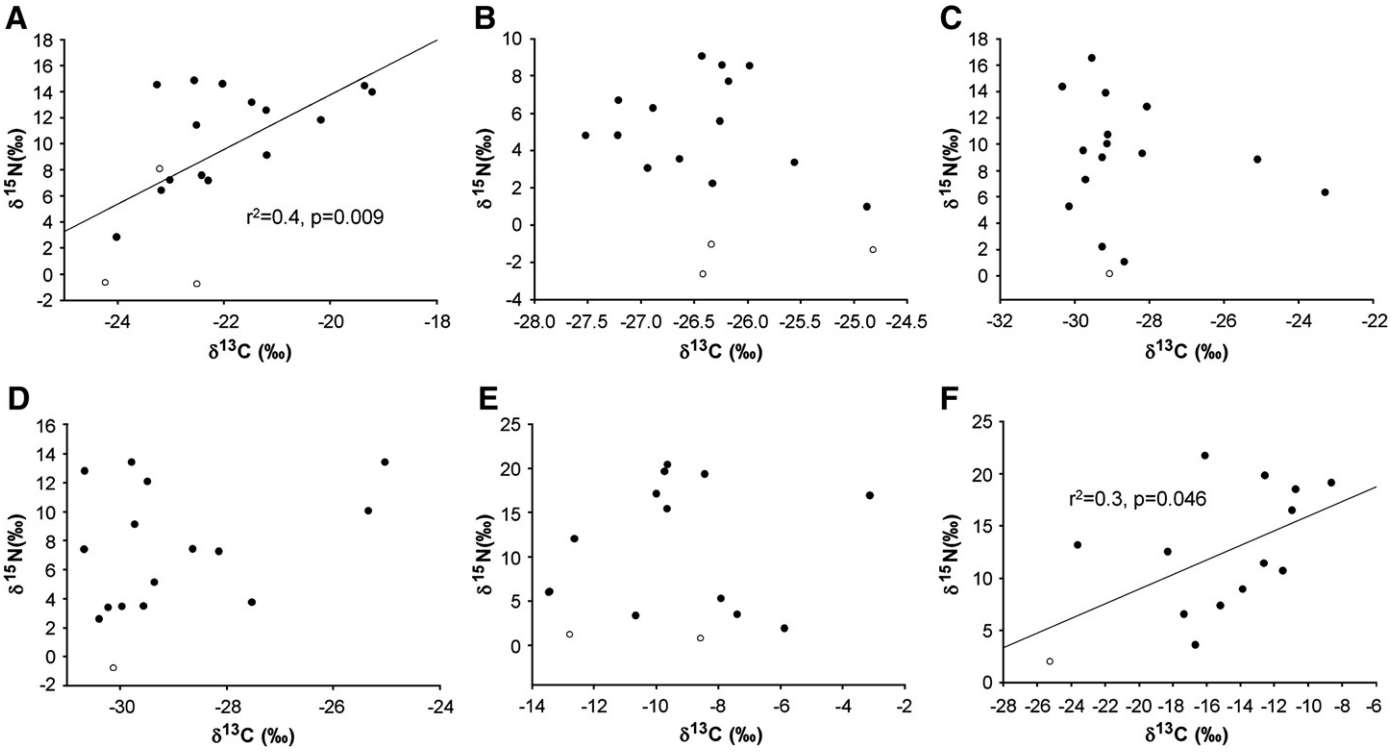

Fig. 6. The relationship between δ^{15}N and δ^{13}C values for A) jewel lichen B) worm lichen C) tufted saxifrage D) purple saxifrage E) periphyton ;and F) zooplankton from Cape Vera. Open symbols represent samples from Cape Hersche r^2 and p values are only reported for significant relationships.

ermine. There was no difference in THg concentrations between the buntings from the reference site and the affected ponds; however, age/sex class had a significant effect on THg concentrations (ANOVA, $F_{2,22}=4.09$, $p=0.03$), with adult males having significantly higher THg concentrations than hatch-year buntings (Tukey HSD test, $p=0.031$). Unfortunately, this is the only study to report THg levels in snow buntings, so we are unable to compare our results to other sites (AMAP, 1998). However, buntings had similar Hg levels as were found in blood of insectivorous songbirds in northeastern North America (Evers et al., 2005). Thus, based on the available data, there appears to be no THg enrichment of Cape Vera buntings.

3.4. THg concentrations in relation to seabird influence

Despite the higher concentrations of THg in pond sediments near the cliffs (Blais et al., 2005), distance from the seabird colony does not appear to have a strong influence on THg concentrations in primary producers around Cape Vera. Contrary to our expectations, periphyton samples collected from ponds farther from the colony had significantly higher THg than those collected close to the cliffs (Fig. 7E; $R^2_{15}=0.49$, $p=0.008$), and this pattern was also observed for the saxifrages and zooplankton, albeit non-significantly (Fig. 7). Moreover, only worm lichen showed a significant correlation between THg concentrations and δ^{15}N values (Fig. 8B; $R^2_{17}=0.40$, $p=0.007$). Of the primary producers, four of the six had positive but non-significant relationships between THg concentrations and δ^{15}N values, whereas the remaining two had negative trends (Fig. 7).

Collectively, we failed to find a consistent relationship between THg concentrations in primary producers and distance from the contamination source, or with δ^{15}N values. Our results may have been confounded by a "biodilution" effect, where increasing biomass and productivity rates of algae can reduce the uptake of mercury to higher trophic levels (Pickhardt et al., 2002). Ponds closer to the seabird colony are characterized by markedly higher primary productivity rates (Brimble et al., 2009). However, we do not believe this was a major factor since THg concentrations were not significantly lower in taxa closer to the colony.

Table 3
Summary of stable isotope, THg mean concentrations and standard errors of several species from Cape Vera, Devon Island, Nunavut and control site Cape Herschel, Ellesmere Island collected from 2005 to 2007 ($n=96$). Significant differences between collection sites are indicated by * (t-test, $p<0.05$).

Sample	N	δ^{15}N (‰)	δ^{13}C (‰)	THg [ng/g dw]
Cape Vera (seabird colony)				
Jewel lichen	15	10.8 ± 0.98*	−21.9 ± 0.37	231 ± 19.0
Worm lichen	14	5.38 ± 0.68*	−26.5 ± 0.19	176 ± 20.8*
Purple saxifrage	15	7.66 ± 1.03	−29.0 ± 0.46	47.9 ± 10.1
Tufted saxifrage	15	9.16 ± 1.12	−28.6 ± 0.50	33.3 ± 3.40
Phyto/zooplankton	13	13.1 ± 1.72	−14.5 ± 1.11	70.8 ± 18.6
Periphyton	13	9.94 ± 1.97*	−9.39 ± 0.82	33.9 ± 6.15
Cape Herschel (control site)				
Jewel lichen	4	1.56 ± 2.18	−23.3 ± 0.50	199 ± 10.3
Worm lichen	3	−1.66 ± 0.49	−25.9 ± 0.52	92.8 ± 11.1
Purple saxifrage	1	−0.76	−30.1	35.1
Tufted saxifrage	1	0.17	−29.1	15.2
Phyto/zooplankton	1	2.03	−25.3	34.6
Periphyton	2	1.01 ± 0.22	−10.7 ± 2.11	13.0 ± 9.58

3.5. Total Hg at Cape Vera and other regions of the Arctic

Because there are relatively few studies that have investigated THg concentrations in a broad trophic range of Arctic biota, it is difficult to make strong inferences on the levels found in the organisms studied at Cape Vera. THg concentrations in taxa from Cape Vera were similar to values found in the same species from Cape Herschel, with only worm lichen having significantly higher concentrations at Cape Vera (Table 2). Mean THg concentrations in jewel and worm lichen from Cape Vera were slightly higher than other Arctic sites. For example, lichen species collected across the circumpolar Arctic averaged 10–100 ng/g (dw), and ranged from 72 to 255 ng/g (dw) for 12 lichen species collected from the Central Barrenlands, Nunavut (AMAP, 1998; Chiarenzelli et al., 2001). Other lichen species (e.g., *Cetraria*

Table 4
Mean total Hg and nitrogen isotope values of several taxa from Cape Vera, Devon Island, Nunavut from 2005 to 2007 ($n = 147$). Significant regression of THg concentrations against δ^{15}N values is indicated by *.

Species	THg [ng/g dw]		δ^{15}N (‰)		r^2	p	N
	Mean ± SE	Range	Mean ± SE	Range			
Worm lichen	161 ± 18.9	72.5–366	4.14 ± 0.88	−2.62–9.07	0.46	0.003*	17
Jewel lichen	226 ± 16.0	133–370	9.37 ± 1.19	−0.62–14.9	0.05	0.37	18
Purple saxifrage	47.1 ± 9.50	15.3–140	7.14 ± 1.10	−0.76–13.4	0.02	0.65	16
Tufted saxifrage	32.2 ± 3.38	15.2–70.8	8.60 ± 1.19	0.17–16.6	0.05	0.41	16
Fungi	247 ± 46.0	151–437	10.7 ± 1.71	6.4–16.8	0.10	0.54	6
Periphyton	31.1 ± 5.71	3.42–68.4	9.94 ± 1.94	0.79–20.4	0.06	0.39	15
Phyto/zooplankton	68.2 ± 17.4	29.9–262	12.3 ± 1.66	2.03–21.8	0.18	0.13	14
Chironomids	58.8 ± 7.17	25.5–101	16.5 ± 1.18	9.71–22.7	0.06	0.44	13
Collared lemming	96.1 ± 63.7	10.3–348	13.7 ± 1.04	10.4–16.8	0.64	0.11	5
Snow bunting	181 ± 27.0	45.9–570	18.1 ± 0.73	10.9–23.2	<0.001	0.96	25
Ermine	202 ± 29.6	172–231	20.3 ± 0.18	20.1–20.4	N/A		2

nivalis) in northern Canada and Greenland had a range of THg from 10 to 270 ng/g (dw) (Crête et al., 1992, Riget et al., 2000). Unfortunately, we are unaware of any published THg contamination studies on jewel or worm lichen specifically. Similarly, most THg concentrations for vascular plants across the Arctic are below detection limits, as were THg levels in *Daphnia* in Alaska (Ford et al., 1995; AMAP, 1998). Furthermore, there are few published THg data for Arctic micro-organisms and insects (AMAP, 1998).

Available information on THg concentrations of small animals collected from the Arctic appears similar to what we found at Cape Vera. THg concentrations in muscle tissue of collared lemmings averaged 70 and 110 ng/g (dw) at two locations in the Taimyr Peninsula of Russia (Allen-Gil et al., 2003), similar to the Cape Vera mean of 96 ng/g. Mercury data for ermine are limited, but the range at Cape Vera (172–231 ng/g) fell within the range found in livers of animals on Banks and Victoria Island, Nunavut [80–650 ng/g ww; (AMAP, 1998)]. However, THg concentrations vary among animal tissues and this must be considered when comparing whole body tissue to liver and muscle (Goldstein et al., 1996; Strom, 2008).

4. Conclusions and future directions

High δ^{15}N in the tissues of terrestrial and aquatic wildlife living in habitats below the cliffs at Cape Vera appears to be clearly linked to fertilization by seabird-derived nutrients deposited by nesting fulmars into local food webs. The elevated δ^{15}N values of many organisms we sampled reached values that are typical of those found in high trophic levels of the marine food web (Dehn et al., 2006). In contrast, δ^{13}C was not enriched, showing little variation among organisms, suggesting that this ratio is not a useful indicator of biovector transport in the terrestrial environment, at least in environments similar to the one we studied here. Total Hg concentrations in worm lichen increased significantly with δ^{15}N values across a gradient of seabird influence, but was the only primary producer to do so. There was no significant relationship between distance from the seabird colony and THg, or between δ^{15}N values and THg in primary producers, and THg concentrations in Cape Vera biota were generally comparable to values found in the same or similar taxa from other Arctic regions.

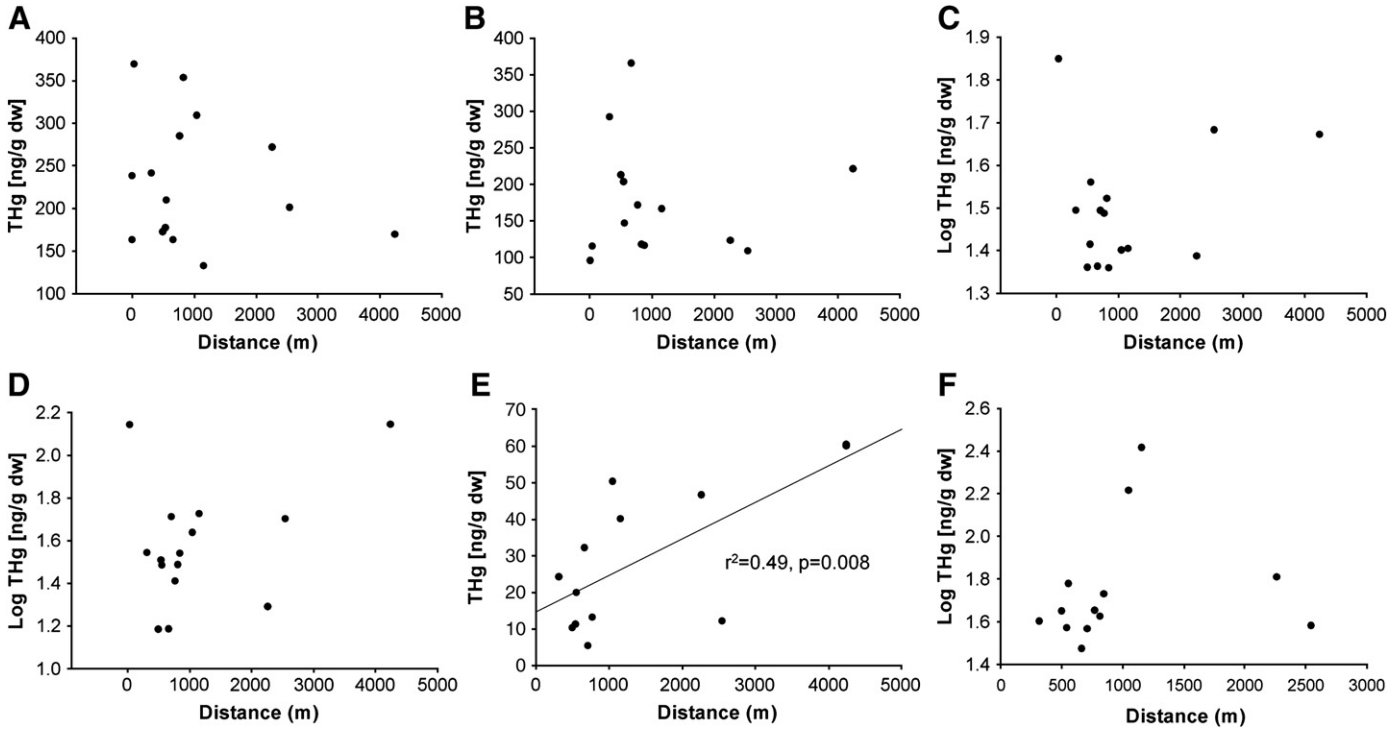

Fig. 7. The relationship between distance from the cliffs and THg concentrations for A) jewel lichen B) worm lichen C) tufted saxifrage D) purple saxifrage E) periphyton and F) zooplankton from Cape Vera r^2 and p values are only reported for significant relationships.

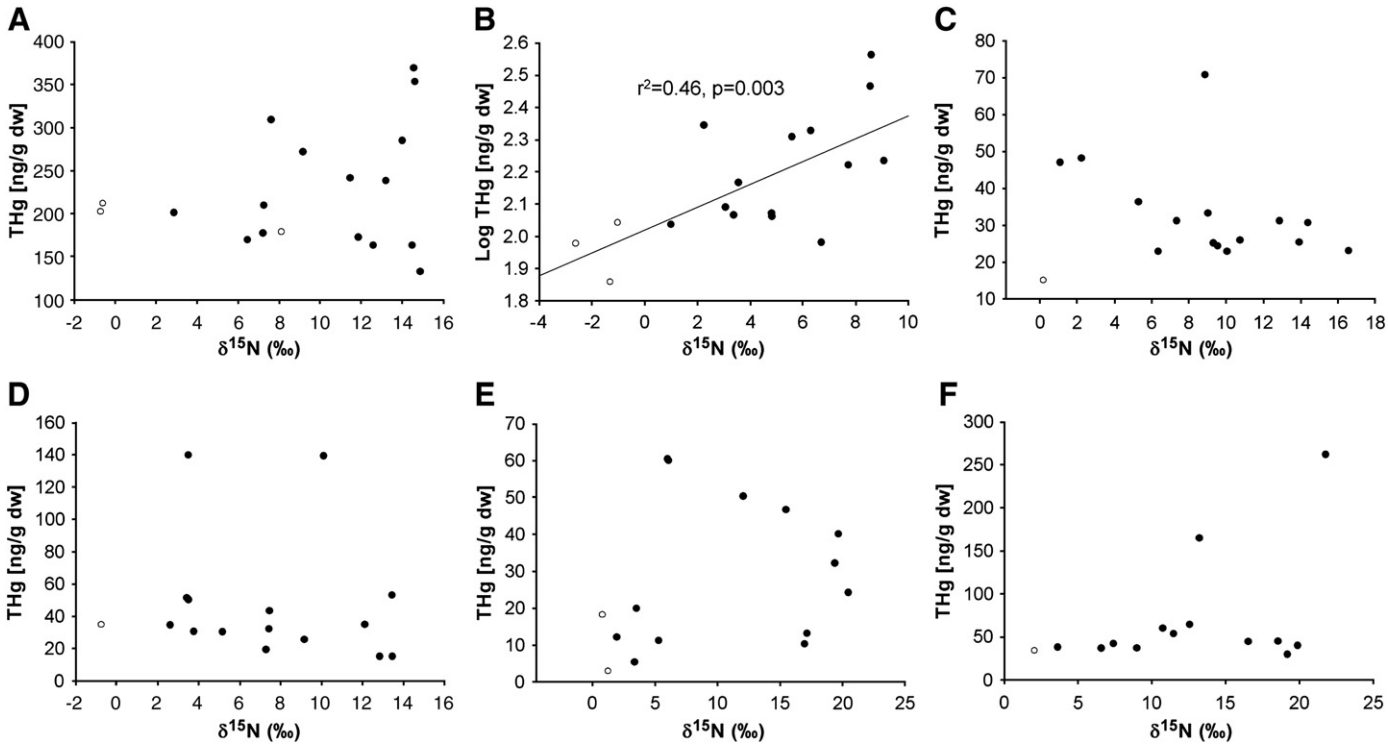

Fig. 8. The relationship between the concentrations of THg [ng/g dw] and δ^{15}N values for A) jewel lichen B) worm lichen C) tufted saxifrage D) purple saxifrage E) periphyton and F) zooplankton from Cape Vera. Open symbols represent samples from Cape Herschel r^2 and p values are only reported for significant relationships.

Unexpectedly, control sites CV1 and CV40 (remote from the seabird cliffs) had high THg concentrations in most samples. These results were corroborated by Brimble et al. (2009), who found high concentrations of other trace metals at CV1 and CV40. Elevated THg concentrations in reference ponds may be explained by hydrologic and geologic variation among sites. Excluding these data from our analyses did not improve the THg and δ^{15}N relationship. Despite the lack of a statistically significant relationship, the highest concentrations of THg for jewel lichen (369.4 ng/g), purple saxifrage (139.6 ng/g), and tufted saxifrage (70.8 ng/g) came from samples of these species taken on the cliff ledge at CV43 (i.e., close to the nesting birds). In contrast, the lowest THg concentrations for tufted saxifrage (15.2 ng/g), periphyton (3.4 ng/g), and worm lichen (72.5 ng/g) were from Cape Herschel, the sampling location without a seabird colony. Consequently, we suspect that factors other than simply distance from the nesting birds or δ^{15}N may be influencing the Hg relationships in the aquatic and terrestrial biota at this location. Future research should examine Hg speciation and measure the concentration of methyl mercury in samples and in seabird guano, which would provide clues to the potential sources of mercury.

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