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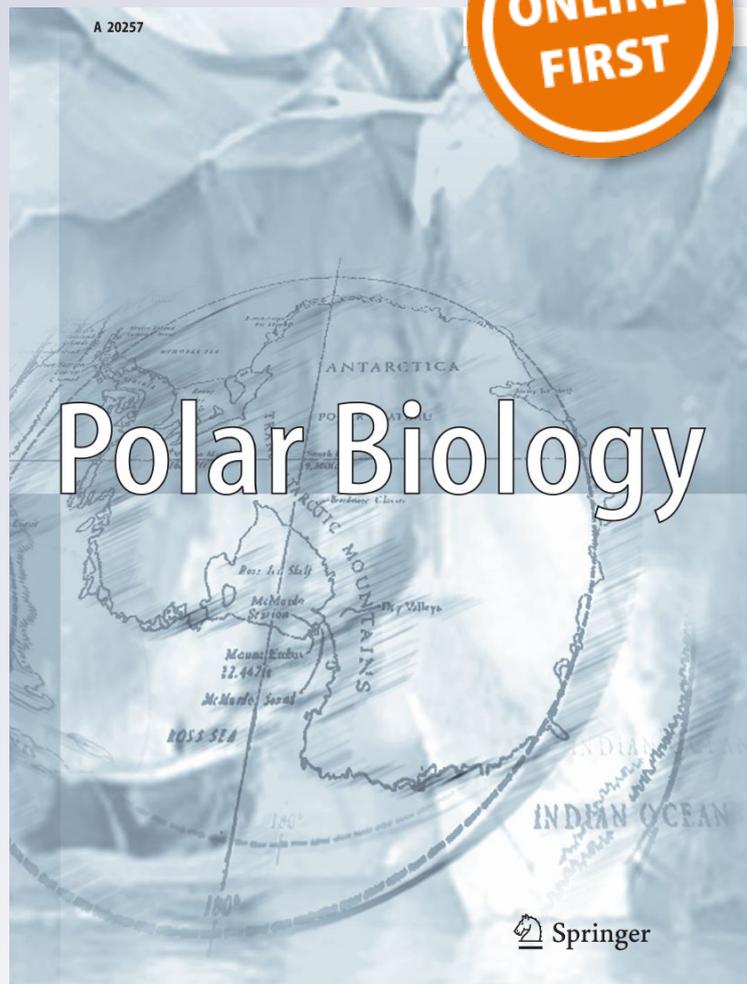
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# Correspondence between mercury and stable isotopes in high Arctic marine and terrestrial avian species from northwest Greenland

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## Abstract

Birds are useful bioindicators of environmental contamination around the globe, but avian studies in the high Arctic have been primarily limited to a few abundant species. This study was designed to assess mercury (Hg) concentrations in both abundant and less-abundant marine and terrestrial avian species on breeding grounds in northwest Greenland using blood sampling. Twenty-four migratory avian species ( $n=625$ ) were sampled over a three-year period (2010–2012) along 750 km of coastline near Thule Air Base (77° N, 68° W). Whole blood samples were analyzed for total Hg along with  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  to estimate food web position. A significant positive correlation was observed between mean Hg concentrations and trophic position, with adult mean Hg concentrations ranging from 11.4 to 1164 ng g<sup>-1</sup> wet weight. Eleven species examined in this study had blood Hg concentrations suggestive of a low risk for Hg toxicity. Some Peregrine Falcon (*Falco peregrinus*), Thick-billed Murre (*Uria lomvia*), and Black Guillemot (*Cepphus grylle*) individuals had concentrations of Hg suggestive of medium risk for Hg toxicity (Hg concentrations between 1000–3000 ng g<sup>-1</sup> ww). Decreasing  $\delta^{15}\text{N}$  values in birds from the central study area suggest a nonuniform geographic pattern of increased freshwater influx and subsequent changes in prey availability, which correspond to lower avian Hg levels. This study provides strong evidence that marine and terrestrial feeding ecology of avian species in NW Greenland contributes to their mercury exposure; however, intraspecific variation in ecology and nesting locations in the region may influence those patterns.

**Keywords** Mercury · Stable isotopes · Arctic · Seabird · Contaminants

## Introduction

The Arctic is increasingly impacted by pollutants, such as trace metals, even though the biome is geographically distant from point sources of pollution in mid and lower latitudes (AMAP 2011b). Mercury (Hg) is a toxic heavy metal that primarily originates in mid- and tropical-latitude

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nations, and is transferred to the Arctic by ocean currents and atmospheric deposition (AMAP 2011b; Beattie et al. 2014; Chen et al. 2015; Obrist et al. 2017). Hg deposited from the atmosphere in its inorganic form is methylated by sulfate-reducing bacteria to form methylmercury (MeHg) in freshwater and marine habitats (Selin 2009). MeHg biomagnifies in the aquatic food chain (Lavoie et al. 2013) and can reach high concentrations in upper trophic-level organisms (Dietz et al. 2000; Sonne 2010) increasing the risk for nervous system damage and reduced reproductive success (for review, see Wolfe et al. 1998; Dietz et al. 2013; Scheuhammer et al. 2015).

Hg has been found at high levels in aquatic and terrestrial species, including birds, in circumpolar Arctic regions (AMAP 1998, 2009, 2011a, 2011b). In fact, a recent study documented higher Hg levels in birds surveyed in the Arctic tundra ecoregion compared to 13 of 15 ecoregions in western North America (Ackerman et al. 2016), and Hg concentrations have increased over time in multiple marine species in Arctic Canada (Braune et al. 2005; Braune 2007; Riget et al. 2011). Among Arctic avian species, seabirds are highly vulnerable to Hg contamination because they occupy a high trophic position (Dietz et al. 2000; Provencher et al. 2014); however, terrestrial birds that feed on aquatic insects emerging from wetlands may also become contaminated with Hg. In addition, minimal data exist quantifying Hg levels in terrestrial-feeding Arctic passerines, shorebirds, birds of prey, and less-abundant Arctic seabird species.

A majority of previous studies quantifying Hg levels in Arctic avian species have focused largely on marine seabird species that occur in high abundance [e.g., Thick-billed Murres (*Uria lomvia*) and Black-legged Kittiwakes (*Rissa tridacta*)]. Tissues such as liver, kidney, and muscle have largely been used for analysis (e.g., Dietz et al. 1997; Riget et al. 1997, 2004), acquisition of which is lethal to sampled birds. Nondestructive techniques have predominantly focused on sampling whole eggs (e.g., Braune et al. 2002; Akearok et al. 2010; Braune et al. 2016) or feathers (e.g., Bond and Diamond 2009b; Fort et al. 2014; Fenstad et al. 2017). Quantification of Hg using these tissue types provides measures of long-term Hg exposure (AMAP 2011a). Whole blood sampling has recently become more common which allows for nondestructive sample collection. Blood is considered the best tissue for evaluating short-term dietary uptake of Hg, and can provide insight into Hg exposure during specific life-history stages or geographic locations at time of sampling (i.e., breeding or wintering grounds) (Evers et al. 2005, 2008; Wayland and Scheuhammer 2011). Furthermore, using nondestructive blood samples allows for sampling of rare and threatened species, for which little-to-no information on Hg exists (Boertmann 2007; Eisler 2010; Croxall et al. 2012). Studies of blood Hg concentrations for Arctic bird species during the breeding season are relatively

uncommon, and recent research has highlighted the overall lack of knowledge of Hg exposure on the breeding grounds of Arctic birds, particularly post egg laying (Braune et al. 2016; Mallory and Braune 2017).

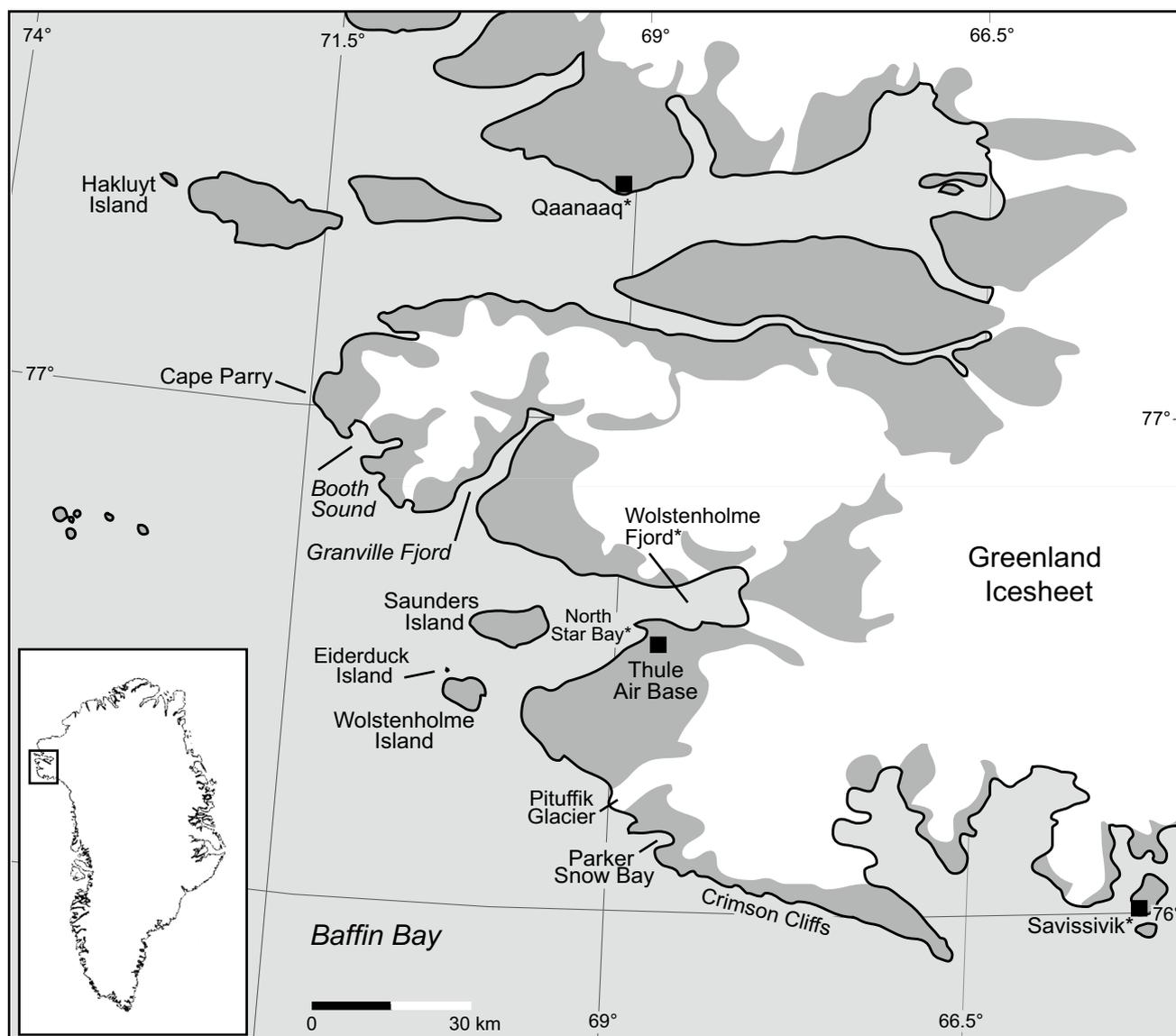
The largest remaining seabird (Boertmann 1994; Boertmann et al. 1996) and waterfowl (Burnham et al. 2012b, 2014) colonies in Greenland are located in the northwest region. This region also has one of the highest avian species diversity in Greenland (Salomonsen 1950; Burnham and Burnham 2010; Burnham et al. 2014), and a number of the species are at the northern extent of their breeding range (Salomonsen 1950; Boertmann 1994; Boertmann et al. 1996). While previous work in Greenland has quantified environmental contaminants, including Hg, in many marine organisms using a variety of tissues (Nielsen and Dietz 1989; Dietz et al. 1996; Riget and Dietz 2000; Riget et al. 2000; Hobson et al. 2002; Campbell et al. 2005; Clayden et al. 2015), we are unaware of studies that have quantified blood Hg concentrations for breeding birds in North Greenland. It is important to note that previous avian studies using non-blood tissues for Hg analysis may represent Hg acquired outside the Arctic because many of the avian species in Greenland are long-distance migrants and spend only a few months in the Arctic each year (Boertmann 1994; Lyngs 2003).

The aim of our study was to establish baseline measurements of avian blood Hg during the post-egg-laying period in northwest Greenland and examine differences across passerine, shorebird, waterfowl, seabird, and bird of prey species, many of which represent knowledge gaps in contamination studies (Mallory and Braune 2012). We used blood sampling to measure Hg concentrations in 24 marine and terrestrial avian species. Stable  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  isotope ratios were also obtained from blood to assess feeding habits and relative trophic position (i.e., biomagnification) (Lavoie et al. 2013) and to examine geographic and temporal patterns. Similar to Hg, stable isotopes measured from the blood reflect short-term dietary intake (Hobson and Clark 1992).

## Methods

### Study area and sampling

Samples were collected in northwest Greenland (between 75°56'N, 66°39'W and 77°11'N, 68°07'W) along 750 km of coastline and its adjacent islands from July 3–August 16, July 9–August 11, and July 5–August 8 in 2010, 2011, and 2012, respectively. The study area, accessed primarily by boat, consists of a narrow coastal region dominated by cliffs and high elevation barren plateaus flanked by the Greenland Ice Sheet and Baffin Bay (Fig. 1). This area forms the eastern



**Fig. 1** Sampling locations and reference place names (indicated by \*) in northwest Greenland. Samples were collected along the coastline between Hakluyt Island in the north to 11 km south of Parker Snow Bay, and at the Booth Sound and Thule Air Base wetland areas

edge of the North Water Polynya. Large regions of prostrate tundra characteristic of the high Arctic are infrequent in the area, but large wetlands exist near Thule Air Base and Booth Sound (Fig. 1). Seabirds and waterfowl nest on cliff faces and multiple islands along the coast, while shorebirds and passerine species were found in the greatest abundance in the wetland areas (Boertmann et al. 1996; Burnham et al. 2012b, 2014). No large commercial trawling fishing operations existed in the area during our study period, and therefore, the diets of studied species were negligibly impacted by scavenging commercial catch. Marine sediments sampled from Thule Air Base (North Star Bay) have been shown to be slightly elevated in Hg, but this was geographically limited to 5–10 km from the base (Glahder et al. 2003) and

therefore not a local Hg source impacting our sampling sites. Marine species studied by Glahder et al. (2003) in North Star Bay (sculpin, cockle, clam, urchin) were not elevated in Hg and therefore present minimal risk to studied seabirds that might feed in the bay and return to our studied colonies.

Blood samples were collected from 24 species that included multiple broadly classified groups identified here as passerines, shorebirds, waterfowl, seabirds, and birds of prey (falcons). Hg concentrations ( $n = 625$ ) and stable isotope values ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ,  $n = 469$ ) were quantified for each species (Table 1). Ten of the 24 species included samples from both adults and juveniles. Sample sizes were largest for species occurring at the greatest abundance (e.g., Thick-billed Murres, Dovekie (*Alle alle*), and Black-legged

**Table 1** Hg and isotope measurements for all bird species sampled in this study

Species	Age	N Hg	Mean Hg $\pm$ SD (ng g <sup>-1</sup> w/w)	Hg range	N isotope	Mean <sup>15</sup> N (‰)	Mean <sup>13</sup> C (‰)	Years
Arctic Tern (ARTE)	Ad.	26	328.61 $\pm$ 141	168.08–632.01	18	14.17	– 19.11	2010/11
<i>Sterna paradisaea</i>	Juv.	–	–	–	–	–	–	–
Atlantic Puffin (ATPU)	Ad.	13	300.31 $\pm$ 68	189.82–396.07	12	14.44	– 19.94	2010/11
<i>Fratercula arctica</i>	Juv.	–	–	–	–	–	–	–
Black Guillemot (BLGU)	Ad.	17	664.39 $\pm$ 189	440.15–1140.51	17	14.47	– 18.69	2010
<i>Cephus grylle</i>	Juv.	–	–	–	–	–	–	–
Black-legged Kittiwake (BLKI)	Ad.	100	269.98 $\pm$ 73	121.29–521.99	86	14.46	– 20.21	2010/11
<i>Rissa tridactyla</i>	Juv.	20	32.76 $\pm$ 12	9.07–62.98	19	13.90	– 21.09	2010/11
Brant Goose (BRGO)	Ad.	1	76.10	–	–	–	–	2010
<i>Branta bernicla</i>	Juv.	–	–	–	–	–	–	–
Canada Goose (CAGO)	Ad.	–	–	–	–	–	–	–
<i>Branta canadensis</i>	Juv.	10	BDL <sup>b</sup>	–	1	5.46	– 27.17	2010
Common Eider (COEI)	Ad. <sup>a</sup>	18	120.10 $\pm$ 38	66.93–220.88	18	11.25	– 19.38	2010/11
<i>Somateria mollissima</i>	Juv.	–	–	–	–	–	–	–
Common Ringed Plover (CRPL)	Ad.	–	–	–	–	–	–	–
<i>Charadrius hiaticula</i>	Juv.	5	BDL <sup>b</sup>	–	–	–	–	2010/12
Dovekie (DOVE)	Ad.	105	193.70 $\pm$ 43	91.01–358.40	71	12.12	– 21.66	2010/11
<i>Alle alle</i>	Juv.	–	–	–	–	–	–	–
Dunlin (DUNL)	Ad.	–	–	–	–	–	–	–
<i>Calidris alpina</i>	Juv.	3	46.61 $\pm$ 25	25.1–74.21	–	–	–	2012
Glaucous Gull (GLGU)	Ad.	13	474.95 $\pm$ 184	202.18–926.59	13	15.29	– 19.09	2010/11
<i>Larus hyperboreus</i>	Juv.	60	273.84 $\pm$ 157	97.82–706.59	44	15.00	– 19.39	2010/11
Gyrfalcon (GYRF)	Ad.	–	–	–	–	–	–	–
<i>Falco rusticolus</i>	Juv.	10	155.68 $\pm$ 132	29.84–416.95	–	–	–	2011/12
Hoary Redpoll (HORE)	Ad.	1	11.42	–	–	–	–	2010
<i>Acanthis hornemanni</i>	Juv.	2	BDL <sup>b</sup>	–	–	–	–	2010
Lapland Longspur (LALO)	Ad.	23	78.36 $\pm$ 61	13.45–225.56	21	6.23	– 24.80	2010/11
<i>Calcarius lapponicus</i>	Juv.	33	21.78 $\pm$ 12	1.15–50.53	21	5.00	– 24.27	2010/11
Long-tailed Duck (LTDU)	Ad. <sup>a</sup>	3	64.34 $\pm$ 13	49.85–74.18	3	12.15	– 19.22	2010
<i>Clangula hyemalis</i>	Juv.	–	–	–	–	–	–	–
Northern Fulmar (NOFU)	Ad.	12	218.54 $\pm$ 110	92.53–486.65	12	14.00	– 20.61	2010
<i>Fulmarus glacialis</i>	Juv.	–	–	–	–	–	–	–
Northern Wheatear (NOWH)	Ad.	1	21.09	–	1	4.31	– 25.53	2010
<i>Oenanthe oenanthe</i>	Juv.	2	11.60	9.87–13.40	2	2.20	– 25.04	2010
Parasitic Jaeger (PAJA)	Ad.	2	543.01	469.38–616.64	1	14.21	– 20.06	2011
<i>Stercorarius parasiticus</i>	Juv.	1	94.11	–	1	12.68	– 20.19	2010
Peregrine Falcon (PEFA)	Ad.	4	1164.85 $\pm$ 368	841.03–1618.28	–	–	–	2011/12
<i>Falco peregrinus</i>	Juv.	23	116.0 $\pm$ 59	50.81–214.01	9	8.32	– 23.25	2010/11/12
Purple Sandpiper (PUSA)	Ad.	4	532.68 $\pm$ 312	192.84–857.79	1	9.18	– 25.68	2010/11/12
<i>Calidris maritima</i>	Juv.	1	149.12	–	1	8.56	– 25.11	2011
Red-necked Phalarope (RNPH)	Ad.	5	246.10 $\pm$ 63	184.89–332.33	4	9.65	– 25.61	2011/12
<i>Phalaropus lobatus</i>	Juv.	–	–	–	–	–	–	–
Red Knot (REKN)	Ad.	1	300.20	–	1	6.31	– 24.91	2010
<i>Calidris canutus</i>	Juv.	11	17.57 $\pm$ 6	9.51–28.25	10	7.24	– 24.31	2010/11
Snow Bunting (SNBU)	Ad.	18	30.12 $\pm$ 28	2.63–87.95	12	6.53	– 23.97	2010/11
<i>Plectrophenax nivalis</i>	Juv.	19	16.40 $\pm$ 13	2.32–44.58	8	5.44	– 23.95	2010/11
Thick-billed Murre (TBMU)	Ad.	61	731.35 $\pm$ 223	389.85–1347.97	60	15.19	– 20.03	2010/11
<i>Uria lomvia</i>	Juv.	–	–	–	–	–	–	–

**Table 1** (continued)<sup>a</sup>All adult females<sup>b</sup>BDL (below detection limit, see methods section), CAGO 80% BDL, CRPL 60% BDL, HORE 50% BDL

Kittiwakes) with smaller numbers of samples collected from less-abundant and uncommon species (e.g., Brant Goose (*Branta bernicla*), Hoary Redpoll (*Acanthis hornemanni*), Dunlin (*Calidris alpina*), Red Knot (*Calidris canutus*), Red-necked Phalarope (*Phalaropus lobatus*), Northern Wheatear (*Oenanthe oenanthe*), Purple Sandpiper (*Calidris maritima*), and Parasitic Jaeger (*Stercorarius parasiticus*)) (Table 1). Data on nesting chronology (Salomonsen 1950; Burnham et al. 2012b, 2014; K. Burnham, unpub. data) were consulted to ensure that blood samples were obtained a minimum of 4 weeks after birds arrived on breeding grounds, and all samples were collected post egg laying. Capture techniques varied by species and included mist net, dip net, noose pole, noose carpet, net gun, and Potter trap. Morphological measurements were recorded with sex discerned only for dimorphic species (e.g., Long-tailed Duck (*Clangula hyemalis*) and Common Eider (*Somateria mollissima*); see Table 1). Blood samples were collected from the brachial vein in large species and from talon clips in smaller species or chicks. A 25 or 27 gauge needle (depending on bird size) was used to collect blood samples, and samples did not exceed 0.1 cc or more than 1% of body weight. Blood samples for Hg analysis (50–140  $\mu$ l depending on bird size) were collected in heparinized capillary tubes and stored frozen until the time of analysis. Blood samples for stable isotope analysis (50–75  $\mu$ l) were collected in microcentrifuge tubes and dried at 40 °C for 24 h. All birds were banded with Danish government bands, measured, and released unharmed.

### Mercury analysis

Whole blood was analyzed for total mercury with a direct Hg analyzer (DMA-80, Milestone Inc., USA). Total Hg was used as a proxy for MeHg as previous studies have found that >90% of total Hg in avian blood is in the form of MeHg (e.g., Rimmer et al. 2005). Quality assurance included reference and duplicate samples. National Research Council of Canada Institute for National Measurement Standards reference samples were analyzed approximately every 10 samples, and the average ( $\pm$  standard deviation) percent recovery was  $101 \pm 1.86\%$  ( $n=47$ ),  $99.7 \pm 3.64\%$  ( $n=39$ ), and  $103 \pm 2.73\%$  ( $n=7$ ) for MESS-3, DOLT-3, and DORM-3, respectively. Duplicate samples were analyzed approximately every 20 samples, and the mean relative percent difference was  $10.4 \pm 11.9\%$  ( $n=29$ ). The limit of detection ranged from 0.17–0.54 ng of Hg over the course of the analysis (i.e.,  $\sim 3$ –10 ng  $g^{-1}$  dw based on the typical sample weight of blood samples). Samples measuring below the detection limit ( $n=24$ ) were recorded as 50% the

detection limit. Mean Hg concentration was not reported for a given species/age-class if <75% of samples were above the detection limit.

### Stable isotope analysis

Approximately 1.0 mg of dried blood was weighed in tin cups (Costech Analytical Technologies, Inc., Valencia, CA) for  $\delta^{15}N$  and  $\delta^{13}C$  analysis using a Costech elemental analyzer (Valencia, CA., USA) coupled to a Delta Plus XP continuous-flow isotope ratio mass spectrometer (Thermo Scientific, Waltham, MA., USA) at the University of Alaska Anchorage Stable Isotope Laboratory. Stable isotope values are reported in delta ( $\delta$ ) notation, relative to international standards (atmospheric nitrogen for  $\delta^{15}N$  and Vienna Pee-dee Belemnite for  $\delta^{13}C$ ). Internal standards (NIST 1547, bowhead whale (*Balaena mysticetus*) baleen, acetanilide, and chicken feathers) were used to determine an accuracy of  $\pm 0.1\%$  for carbon and  $\pm 0.2\%$  for nitrogen. Ten internal standards were run for each 40 unknown samples, five before and after the unknowns were analyzed.

The majority of samples were analyzed for both Hg and stable isotopes, but a few individuals were analyzed for only Hg when insufficient blood was available for both analyses. Student's *t* tests (equal variances tested for and tests ran accordingly) or Mann–Whitney *U* tests (when distribution of data were not normal) were used to test for differences (within species) in blood Hg concentrations,  $\delta^{15}N$  and  $\delta^{13}C$  between years, sexes (when known), and geographical sampling locations. Tests for relationships between Hg concentration and geographic sampling location were performed only for species with five or more adults sampled at two or more locations. In instances when samples were obtained from greater than two geographical locations in a single year, an analysis of variance (ANOVA) test was used followed by Tukey's HSD post hoc tests, as appropriate. Linear regression was used to test for relationships between Hg concentration and  $\delta^{15}N$  and  $\delta^{13}C$  ratios, and relationships between sample date and Hg concentration were tested using Pearson correlation coefficient. Statistical analyses were conducted using Minitab (State College, Pennsylvania).

### Results

Adult mean blood Hg concentrations ranged from 11.4 ng  $g^{-1}$  in Hoary Redpoll to 1164.85 ng  $g^{-1}$  in Peregrine Falcon (*Falco peregrinus*) (Table 1, Fig. 2). Based

on classified group, birds of prey had the highest Hg concentration (least squares mean =  $1164.85 \pm 368 \text{ ng g}^{-1}$ ) followed by seabirds ( $413.87 \pm 97 \text{ ng g}^{-1}$ ), shorebirds ( $359.68 \pm 152 \text{ ng g}^{-1}$ ), waterfowl ( $86.85 \pm 29 \text{ ng g}^{-1}$ ), and passerines ( $35.25 \pm 30 \text{ ng g}^{-1}$ ).

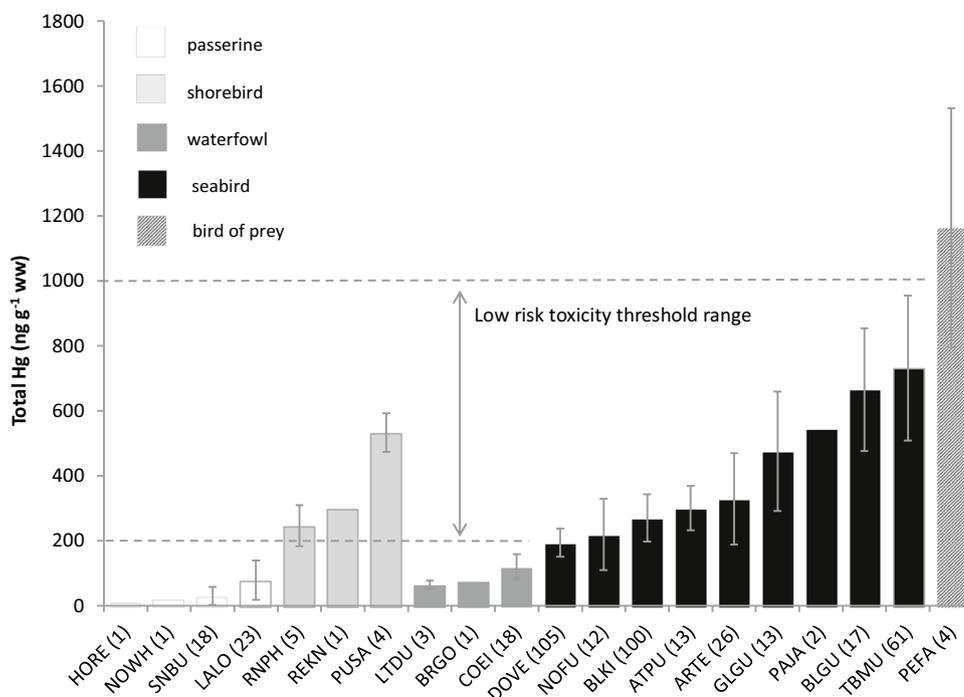
In the ten species for which adults and juveniles were both sampled, blood Hg concentrations were higher in adults in all cases (Table 1). In the five species which had >4 adults and juveniles sampled, Hg concentrations were significantly higher in adult Black-legged Kittiwake (Student's *t* test,  $t_{117} = 30.51$ ,  $p < 0.001$ ), Glaucous Gull [(*Larus hyperboreus*), Mann-Whitney,  $U = 628$ ,  $p = 0.003$ ], Lapland Longspur [(*Calcarius lapponicus*), Mann-Whitney,  $U = 102$ ,  $p < 0.001$ ], and Peregrine Falcon (Student's *t* test, data log transformed,  $t_{25} = 8.85$ ,  $p < 0.001$ ). Only adult and juvenile Snow Bunting (*Plectrophenax nivalis*) did not have a significant difference in Hg (Mann-Whitney,  $U = 124$ ,  $p = 0.235$ ). The remaining five species had low sample sizes or less than 75% of samples were above the detection limit, and thus statistical comparisons were not done. Adult Red Knots had the highest concentrations of Hg compared to juveniles (17.1x) and Glaucous Gulls had the lowest (1.7x) (Table 1). The observed range is consistent with previous studies that also documented 5 to 10x higher Hg levels in adult compared to juvenile birds in northeastern North America (Evers et al. 2005).

$\delta^{13}\text{C}$  values in adults ranged from  $-25.7$  (Purple Sandpiper) to  $-18.7\text{‰}$  [Black Guillemot (*Cephus grylle*)

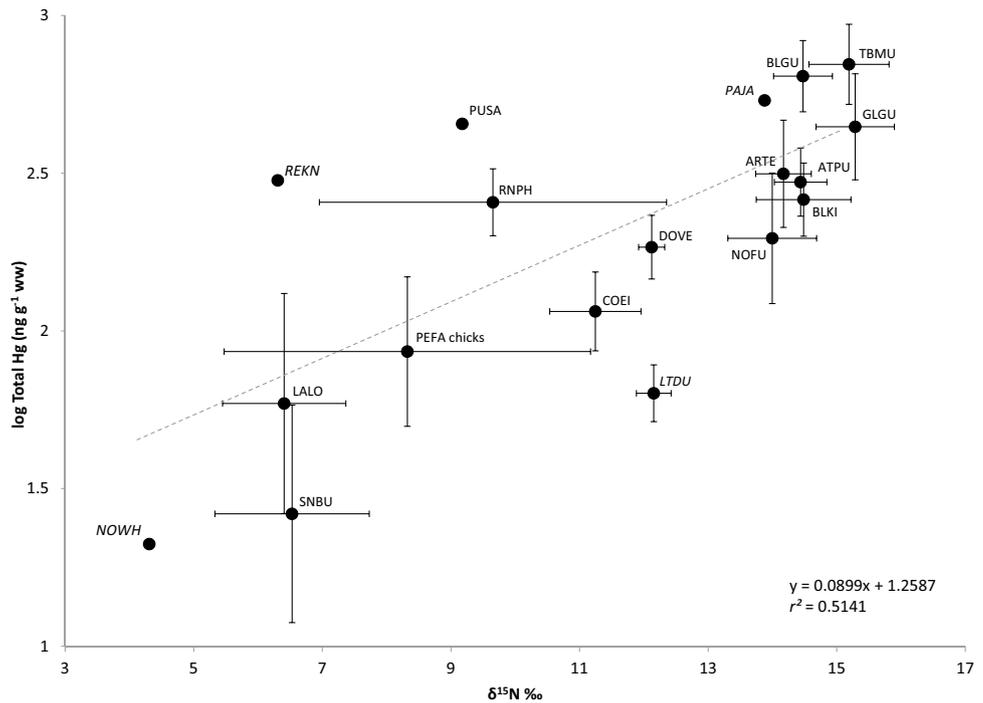
and  $\delta^{15}\text{N}$  values ranged from 4.3 (Northern Wheatear) to 15.3‰ (Glaucous Gull) (Table 1). The most depleted  $\delta^{15}\text{N}$  values were observed in passerines and the most enriched  $\delta^{15}\text{N}$  values in seabirds.  $\delta^{15}\text{N}$  values are cautiously interpreted here as a proxy for trophic position, and  $\delta^{13}\text{C}$  provides insight into where species forage (e.g., marine, near shore, terrestrial environments, etc.).

Concentrations of Hg in blood of marine and terrestrial species in northwest Greenland exhibited a significant positive correlation with  $\delta^{15}\text{N}$  ( $r^2 = 0.51$ ,  $p = 0.004$ , slope = 0.089,  $n = 346$ ) (Fig. 3). Thick-billed Murres (pelagic and benthic fish-feeding seabird) had the highest Hg concentration (mean =  $731.35 \pm 223 \text{ ng g}^{-1}$ ) and second highest trophic level (Peregrine falcons had highest overall Hg concentrations, but isotopic data was not available for comparison). The highest trophic position for Glaucous gulls (coastal scavenger and predator) corresponded to the fifth highest Hg concentration (Fig. 3).  $\delta^{13}\text{C}$  was also significantly correlated with Hg concentrations in blood ( $r^2 = 0.14$ ,  $p = 0.001$ , slope = 0.062,  $n = 346$ ) (Fig. 4) indicating that marine-feeding species had higher Hg concentrations than terrestrial-feeding species. As with adults, concentrations of Hg in the blood of juvenile marine and terrestrial avian species in northwest Greenland exhibited a significant positive correlation with  $\delta^{15}\text{N}$  ( $r^2 = 0.51$ ,  $p = 0.031$ , slope = 0.083,  $n = 106$ ) (Online Resource 1).  $\delta^{13}\text{C}$  was not significantly correlated with Hg ( $r^2 = 0.30$ ,  $p = 0.123$ , slope = 0.129,  $n = 106$ ) (Online Resource 2).

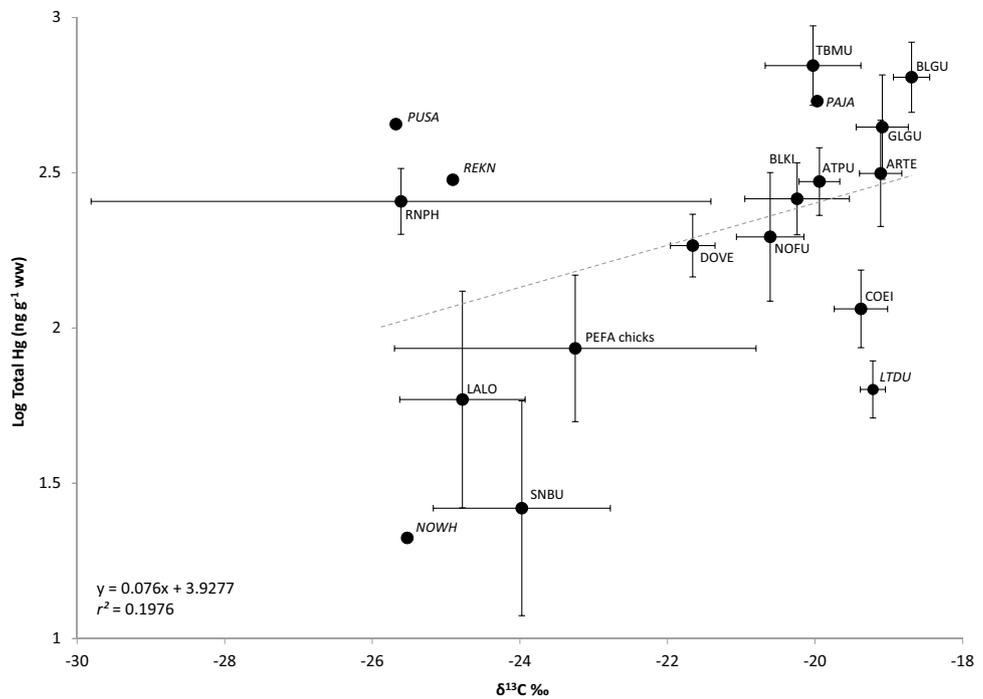
**Fig. 2** Whole blood total mercury ( $\pm$ SD) for adult birds ranked by mean Hg concentration grouped by bird type. Species not included had juvenile-only samples. Toxicity threshold shown as dashed lines (from Ackerman et al. 2016). Sample size in parenthesis and four letter species codes defined in Table 1



**Fig. 3** Mean and SD for  $\delta^{15}\text{N}$  and Hg in all adult birds. Higher  $\delta^{15}\text{N}$  values indicate higher trophic positions. Data shown are only for samples run for both Hg and isotopes (sample sizes differ from Table 1). Hatch year Peregrine Falcons (PEFA chicks) shown, but not included in linear regression statistic. Four letter species codes defined in Table 1. Species codes in *italics* indicate species that are represented by fewer than five samples



**Fig. 4** Mean and SD for  $\delta^{13}\text{C}$  and Hg in adult birds.  $\delta^{13}\text{C}$  values reflect dietary carbon source, with less enriched values indicating terrestrial sources and more enriched values indicating marine sources. Data shown are only for samples run for both Hg and stable isotopes. Hatch year peregrine falcons (PEFA chicks) shown, but not included in the linear regression statistic. Four letter species codes defined in Table 1. Species codes in *italics* indicate species that are represented by fewer than five samples



**Discussion**

Our study documents low to moderately high levels of Hg in bird populations in northwest Greenland. Although there are relatively few comparative blood Hg studies of the same Arctic species on breeding ground, our compared

mean Hg results were mixed (Table 2). Concentrations of blood Hg in Arctic Terns (*Sterna paradisaea*) and Atlantic Puffins (*Fratercula arctica*) measured in our study were 2x higher than breeding birds reported at a more southern latitude (New Brunswick, Canada, 44° N) (Bond and Diamond 2009a) (Table 2). Studies of Black-legged Kittiwakes nesting in Svalbard (similar latitude) reported both

lower and slightly higher mean Hg levels than were found in our study (Goutte et al. 2015; Tartu et al. 2015; respectively). Dovekies nesting farther south in east Greenland had a lower Hg concentration (Fort et al. 2014; Table 2). These results are similar to those found by Braune et al. (2002, 2006, 2014a, 2014b), who suggested that Hg concentration in Arctic seabird populations increase with latitude (although blood samples were not the method of comparison). Among non-seabird species only Common Eiders and Red-necked Phalarope had comparable blood Hg data published. Wayland et al. (2001) and Provencher et al. (2016) studied Common Eiders nesting farther south in eastern Canada and reported mean Hg concentrations nearly 2x higher than in our study, which is similar to the decreasing latitudinal pattern reported for Common Eider in the eastern Canadian Arctic by Mallory et al. (Mallory et al. 2004; not blood samples). A single Red-necked Phalarope sample in coastal northern Alaska was substantially higher (Perkins et al. 2016) than our reported values. While concentrations of Hg in other tissue types have been published for a number of the species studied here, useful comparisons with blood tissue are challenging due to differences in heavy metal retention between tissue types and demethylation rates between tissue type and species (Eagles-Smith et al. 2008).

Although toxicity thresholds for Hg concentrations in avian blood have been developed for a few species in laboratory settings [e.g., Ring-necked Pheasants (*Phasianus colchicums*) and Mallards (*Anas platyrhynchos*) (Fimreite 1971; Heinz 1976)] and in field conditions at lower latitudes (Fisk et al. 2005; Evers et al. 2008), only a few studies have identified toxicity effects of Hg among species that exist in the high Arctic. Tartu et al. (2013, 2015) reported reduced reproductive success and less-frequent breeding attempts among Black-legged Kittiwakes in Svalbard with whole blood equivalent concentrations of total Hg of 300–400 ng g<sup>-1</sup> (see Ackerman et al. 2016 for conversion). Braune et al. (2012) documented decreased egg hatchability with Thick-billed Murre and Arctic Tern eggs injected with MeHg at whole blood equivalent concentrations of 1200 and 2500 ng g<sup>-1</sup>, respectively (see Ackerman et al. 2016 for conversion). While the adult Black-legged Kittiwake mean Hg concentration in our study was below the concentrations that resulted in adverse fitness effects in Tartu et al. (2013, 2015), maximum Hg concentrations for 27% ( $n = 27/100$ ) of the sampled individuals met or exceeded those levels, and may warrant further investigation.

Broadly speaking across latitudes and species, total Hg concentrations of 200–1000 ng g<sup>-1</sup> have been observed to pose low fitness risks, 1000–3000 ng g<sup>-1</sup> moderate risks, and values exceeding 3000 ng g<sup>-1</sup> pose high and

**Table 2** Comparison of blood Hg concentrations for species studied in northwest Greenland from multiple studies. Comparative values are also based on wet weight measurements

Species	Mean Hg (ng g <sup>-1</sup> )	Location	Tissue	N	Year	Source
Arctic Tern	329	76°N, 68°W	blood	26	2010/11	This paper
	163	44°N, 67°W	blood	29	2005/06	Bond and Diamond 2009a
Atlantic Puffin	300	76°N, 68°W	blood	13	2010/11	This paper
	176	44°N, 67°W	blood	17	2005/06	Bond and Diamond 2009a
Black-legged Kittiwake	270	76°N, 68°W	blood	100	2010/11	This paper
	284 <sup>a</sup>	79°N, 12°E	blood	130	2012	Tartu et al. 2015
	199	78°N, 12°E	blood <sup>b</sup>	105	2008/09	Goutte et al. 2015
Common Eider	120	76°N, 68°W	blood	18	2010/11	This paper
	~120 <sup>c</sup>	79°N, 12°E	blood	29	2011	Fenstad et al. 2017
	210 <sup>d</sup>	64°N, 82°W	blood	193	2013/14	Provencher et al. 2016
	230	64°N, 81°W	blood	26	1997/98	Wayland et al. 2001
	~170 <sup>c</sup>	60°N, 23°E	blood	28	2011	Fenstad et al. 2017
Dovekie	51	44°N, 67°W	blood	4	2005/06	Bond and Diamond 2009a
	194	76°N, 68°W	blood	105	2010/11	This paper
Red-necked Phalarope	177 <sup>a</sup>	71°N, 22°W	blood	64	2010/11	Fort et al. 2014
	246	76°N, 68°W	blood	5	2011/12	This paper
	1210	71°N, 157°W	blood	1	2009	Perkins et al. 2016

<sup>a</sup>Converted from dry weight to wet weight using 79% moisture content for blood (Eagles-Smith et al. 2008)

<sup>b</sup>Blood equivalent value from original tissue of red blood cells (converted by Ackerman et al. 2016)

<sup>c</sup>Median value interpreted from figure, as mean was not provided in the text

<sup>d</sup>Samples collected on breeding grounds prior to egg laying

severe risks (Ackerman et al. 2016). The mean Hg concentration of all but one of our studied species falls at or below the low toxicity impact level (Fig. 2). The Peregrine Falcon was the only species with mean Hg concentrations  $> 1000 \text{ ng g}^{-1}$  indicating moderate risk from Hg exposure (mean =  $1164 \pm 368 \text{ ng g}^{-1}$ ). However, 8 of 61 (13.1%) Thick-billed Murres and 1 of 17 (5.9%) Black Guillemots had Hg concentrations  $> 1000 \text{ ng g}^{-1}$  suggesting that all three species may warrant further investigation concerning potential fitness effects. Eleven species had mean concentrations associated with low risk to Hg toxicity (including Thick-billed Murres and Black Guillemots) while an additional four species had individuals in this range (Table 1). Avian species of concern listed in *Greenland's Red List* (Boertmann 2007) as vulnerable (Common Eider, Thick-billed Murre, and Black-legged Kittiwake) and near threatened (Atlantic Puffin, Gyrfalcon (*Falco rusticolus*), and Arctic Tern) may also warrant special attention and continued monitoring. Special attention may also be warranted for three species designated by The Arctic Council Working Group, Conservation of Arctic Flora and Fauna (CAFF), as species of circumpolar concern: Long-tailed Duck, Dunlin, and a Red Knot subspecies (*C. c. islandica*) (Johnston et al. 2015). We were only able to obtain blood samples from Gyrfalcon chicks, and therefore, efforts should be made to quantify Hg concentrations in adult Gyrfalcons to determine if they accumulate high levels of Hg similar to Peregrine Falcons as shown in this study.

## Observed patterns by bird group

### Passerines

Snow Buntings and Lapland Longspurs had some of the lowest  $\delta^{15}\text{N}$  values reflecting their low trophic level feeding behavior (insects and seeds). Although these terrestrial birds generally had low Hg levels and minimal toxicity risks, some individuals exhibited Hg concentrations that approached those of the seabirds (i.e., the highest values for Lapland Longspurs approached the mean values for Northern Fulmars (*Fulmarus glacialis*), and the highest values for Snow Buntings approached the lowest values of Dovekies) (Table 1). The large standard deviation in Hg concentration of these passerines might be explained by diet variations or sex (Savoy 2004; Jaeger et al. 2009). Little is known about Hg levels in Arctic passerines, so circumpolar or latitudinal comparative analyses were not possible.

Lapland Longspurs and Snow Buntings sampled in the wetlands at Thule Air Base showed significant inter-annual Hg variation between 2010 and 2011. Lapland Longspurs had more Hg in 2011 (mean =  $102.2 \text{ ng g}^{-1}$ ,  $n = 15$ ) than in 2010 (Student's  $t$  test,  $t_{17} = 3.83$ ,  $p = 0.001$ ; mean =  $33.65 \text{ ng g}^{-1}$ ,  $n = 8$ ) and similarly Snow Buntings had higher

mean Hg in 2011 (mean =  $51.7 \text{ ng g}^{-1}$ ,  $n = 7$ ) than in 2010 (Mann–Whitney,  $U = 15$ ,  $p = 0.004$ ; mean =  $16.4 \text{ ng g}^{-1}$ ,  $n = 11$ ). Hg variation in these passerines may be influenced by the timing of sampling during our study. The trapping season was 3 weeks longer in 2010 and Hg in Snow Buntings declined throughout the season ( $r^2 = 0.690$ ,  $p < 0.002$ ,  $n = 11$ ), with low Hg concentrations obtained from individuals late in the season greatly reducing the mean. This pattern appears to be similar for Lapland Longspurs, although the relationship between Hg concentration and sample date was not significant ( $r^2 = 0.328$ ,  $p = 0.138$ ,  $n = 8$ ), likely the result of too few samples and a six-day shorter sampling period than for Snow Buntings.

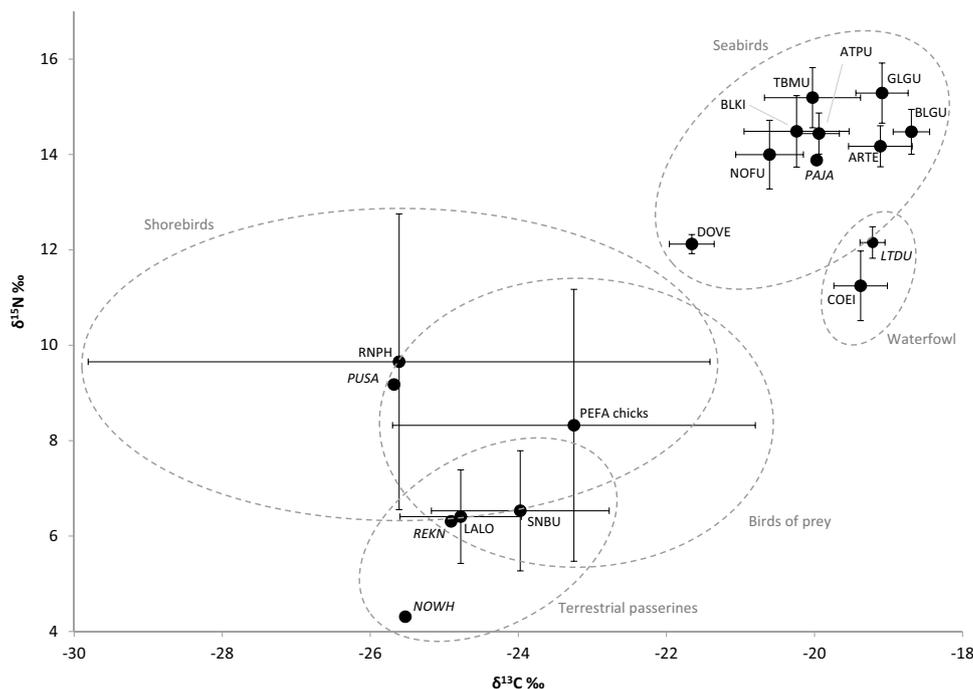
Snow Buntings and Lapland Longspurs were among the few sampled species for which plumage was used to determine sex. For both species, adult males had higher mean blood Hg concentrations than females, although not significantly (SNBU, Student's  $t$  test,  $t_{16} = 1.08$ ,  $p = 0.295$ ,  $38.9 \pm 35.5$ ,  $n = 7$  vs.  $24.52 \pm 21.44$ ,  $n = 11$ ; LALO, too few samples for meaningful statistics,  $83.3 \pm 64.8$ ,  $n = 19$  vs.  $54.9 \pm 50.2$ ,  $n = 4$ ; respectively). These results may be expected as experiments dosing egg-laying female Coturnix Quail (*Coturnix coturnix*), Mallards, and Corey's Shearwaters (*Calonectris borealis*) with Hg demonstrated egg laying as an important method of Hg excretion (Lewis and Furness 1993; Monteiro and Furness 2001; Heinz and Hoffman 2004). Samples in our study were collected post egg laying, which *could* result in females having lower Hg levels than males. Although sex was not a major component of this study, it could be expanded in the future to better explain observed Hg variation within species.

### Shorebirds

Red-necked Phalarope and Purple Sandpiper had a slightly higher trophic position than passerines (Fig. 3), but were still isotopically distinct from marine-feeding birds (Fig. 5). Red-necked Phalarope spend their nonbreeding season in a marine environment and then move to a terrestrial environment for breeding (Rubega et al. 2000). The timing of our sampling was unique in that it revealed isotopic values (note wide error bars for  $\delta^{13}\text{C}$  in Fig. 5) that reflect the transition in diet from marine-based prey (isotopically enriched) to a terrestrial-based diet (isotopically depleted) (Morrison and Hobson 2003).

An unexpectedly high Hg concentration ( $532.68 \pm 312 \text{ ng g}^{-1}$ ) was observed in Purple Sandpiper given its trophic position (Figs. 2, 3). Red-necked Phalarope, another shorebird species, also exhibited a similar pattern (mean =  $246.10 \pm 63 \text{ ng g}^{-1}$ ). Both species are known to feed on emergent aquatic insects that can elevate Hg levels higher than would be expected with a terrestrial diet (Gerard and St. Louis 2001; Jackson et al. 2011), and Arctic

**Fig. 5** Whole blood  $\delta^{13}\text{C}$  versus  $\delta^{15}\text{N}$  ( $\pm$ SD) for adult birds. Note the clear separation between marine feeding seabirds and waterfowl (more enriched  $^{15}\text{N}$  and  $^{13}\text{C}$ ) and terrestrial feeding passerines (less enriched  $^{15}\text{N}$  and  $^{13}\text{C}$ ). Shorebirds and Peregrine Falcon chicks occupy an intermediate isotopic range reflecting a mixed diet of greater isotopic variability. Four letter species codes defined in Table 1. Species codes in *italics* indicate species that are represented by fewer than five samples



lakes and wetlands habitats may expose birds to harmful levels of MeHg (AMAP 2011a). Hargreaves et al. (2010) and Perkins et al. (2016) suggest potentially detrimental Hg levels are extensive across Arctic-breeding shorebirds in northern Canada and western Alaska, respectively. The large standard deviation in Hg concentration in Purple Sandpipers (Table 1) also warrants further investigation as the highest Hg levels approach the detrimental levels noted by Perkins et al. (2016) for similar shorebird species. All individuals ( $n=5$ ) were sampled from the same site, but sex (unknown) might provide insight into this variability.

### Waterfowl

Waterfowl, including the Common Eider and Long-tailed Duck, exhibited lower than anticipated Hg levels (mean =  $120.10 \pm 38$  and  $64 \pm 13$  ng g<sup>-1</sup>, respectively) for their trophic position (Fig. 3). Both species have a benthic mollusk-based diet that has been shown to correspond with lower trace contaminant levels (Nielsen and Dietz 1989). This diet is reflected as isotopically distinct from other sampled bird groups in the study area (Fig. 5). Common Eider hens fast during incubation, but they feed near their breeding site for 4–6 weeks before laying (Gorman and Milne 1971; Parker and Holm 1990) and thus their Hg load is largely representative of local acquisition. Although lower than anticipated Hg levels could indicate low risk to Common Eiders, Wayland et al. (2008) suggests caution when using single year blood measurements to evaluate Hg risk in long-lived waterfowl.

### Birds of prey

Adult Peregrine Falcons had not only the highest mean Hg concentration reported during our study, but also the single highest Hg concentration of any individual bird measured ( $1618.28$  ng g<sup>-1</sup>). Research on American Kestrels (*Falco sparverius*), frequently used as a proxy or surrogate for Peregrines and other raptors in contaminant studies in captive populations (Bardo and Bird 2009), revealed they are extremely susceptible to the effects of Hg, with significant effects on egg production, incubation performance, hatchability, and fledging success as Hg levels increased (Albers et al. 2007). Furthermore, Albers et al. (2007) suggested that American Kestrels may be more susceptible to Hg accumulation in eggs than non-birds of prey. Peregrine Falcons in our study area are increasing in population (Burnham et al. 2012a), but continued monitoring is warranted given the potentially toxic Hg levels observed.

Falcon chicks, although perceived as a top predator, sit in a mid-level trophic position (Fig. 5). This is likely a result of prey delivery variations by nest, with some nests provisioned almost exclusively on seabirds (Dovekies or Black-legged Kittiwakes) and other passerines (Snow Buntings and Lapland Longspurs) (Burnham 2008; Burnham et al. 2012a). This is highlighted by the large differences in mean  $\delta^{15}\text{N}$  values for the three different nests sampled in this study:  $11.67 \pm 0.04$ ,  $8.19 \pm 0.05$  and  $5.10 \pm 0.43$  ‰ (three chicks sampled at each nest) (note wide error bars in Fig. 5). Isotope measurements were not made on adults, but will be included in future studies.

## Seabirds

Marine feeding birds (enriched  $\delta^{13}\text{C}$ ) exhibit distinct isotopic separation from terrestrial-feeding and shorebird species (more depleted  $\delta^{13}\text{C}$ ) (Fig. 5). Dovekies were slightly separated from the larger marine feeding group, reflecting a slightly lower trophic level and a diet of copepods and amphipods (less enriched  $\delta^{13}\text{C}$ ) (Roby et al. 1981; Pederson and Falk Pedersen and Falk 2001; Frandsen et al. 2014). Seabirds had the second highest mean Hg levels ( $413.87 \pm 97 \text{ ng g}^{-1}$ ) after birds of prey (Peregrine Falcon), with Dovekies having the lowest mean and Thick-billed Murres having the highest (Fig. 2). Three seabird species: Thick-billed Murre (mean =  $731.35 \pm 223 \text{ ng g}^{-1}$ ), Parasitic Jaegers (mean =  $543.01 \text{ ng g}^{-1}$ ) and Black Guillemots (mean =  $664.39 \pm 189 \text{ ng g}^{-1}$ ) had above expected Hg levels compared to relative trophic position. These levels could be explained by diet or changes in diet (as reflected in  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ). Spatial and temporal variations in Hg and stable isotopes were assessed for adults from three seabird species (Black-legged Kittiwake, Dovekie, and Thick-billed Murre) with  $n > 5$  samples from more than one location in the same year.

**Black-legged Kittiwakes** Black-legged Kittiwakes were sampled at three geographically distinct colonies (Hakluyt Island, Saunders Island, and Parker Snow Bay) in 2010 and 2011. Kittiwakes showed spatial variation in Hg between the three locations sampled in 2011 (ANOVA,  $F_{(2,51)} = 4.05$ ,  $p = 0.023$ ), although a post hoc Tukey test showed only samples from Hakluyt Island (mean =  $336.54 \text{ ng g}^{-1}$ ,  $n = 14$ ; northern edge of study area, Fig. 1) and Saunders Island (mean =  $270.87 \text{ ng g}^{-1}$ ,  $n = 35$ ; central study area) to be significantly different ( $p = 0.037$ ). Inter-annual Hg comparisons were only available for Saunders Island, and were not significantly different (Mann–Whitney,  $U = 406$ ,  $p = 0.829$ ) between 2010 and 2011 ( $258.8 \pm 48.5 \text{ ng g}^{-1}$  and  $270.9 \pm 82.2 \text{ ng g}^{-1}$ , respectively).

To help explain these Hg patterns, we looked at corresponding stable isotope samples. The most consistent spatial pattern in isotopes was a significant difference in  $\delta^{15}\text{N}$  between all three colonies in 2011 (Online Resource 3). The Saunders Island colony (geographically central) had the most depleted mean  $\delta^{15}\text{N}$  (14.0‰), followed by Hakluyt Island (northern-most) (15.0‰), and Parker Snow Bay (southern-most) (15.7‰), which produced neither a latitudinal nor longitudinal gradient.  $\delta^{13}\text{C}$  colony differences were less clear with a significant difference observed only between Parker Snow Bay and Saunders Island (2010 more depleted at Parker Snow Bay and 2011 more depleted at Saunders Island), and between Saunders Island and Hakluyt Island in 2011 (more depleted at Saunders) (Online Resource 3). Significant inter-annual differences in  $\delta^{15}\text{N}$

(depletion) were observed between 2010 and 2011 for both Saunders Island and Parker Snow Bay (Online Resource 3). Causey et al. (2013) noted a similar pattern with combined blood and feather samples from these colonies. Inter-annual differences in  $\delta^{13}\text{C}$  were significant only for Saunders Island, which became more depleted between 2010 and 2011 (Online Resource 3). Causey et al. (2013) suggest the more depleted samples from 2011 are due to consumption of prey items like herbivorous plankton and juvenile cod that occupy a lower trophic position.

Differences in foraging areas can also contribute to variations in Hg. While no foraging area information is available specific to our study area for Black-legged Kittiwakes, information from a colony to the south showed that adults primarily forage within 30 km of the colony (Frederiksen et al. 2017). With distances between colonies in our study area ranging from 57 to 177 km (Hakluyt to Saunders = 117 km, Saunders to Parker Snow Bay = 57 km, and Hakluyt to Parker Snow Bay = 177 km), foraging-area overlap between colonies is likely minimal.

**Dovekies** Statistical analysis of Hg and isotopic differences between Dovekie colonies was limited to two sampling sites in 2011 [Hakluyt Island ( $n = 14$ ) and Crimson Cliffs ( $n = 21$ )] (Fig. 1). Dovekies sampled near Hakluyt Island (mean  $167.2 \text{ ng g}^{-1}$ ,  $n = 18$ ) were not significantly different in Hg from those sampled at Crimson Cliffs (Student's  $t$  test,  $t_{36} = 1.84$ ,  $p = 0.074$ ; mean =  $189.7 \text{ ng g}^{-1}$ ,  $n = 23$ ).  $\delta^{15}\text{N}$  values (Hakluyt mean = 12.2‰, Crimson Cliffs mean = 12.16‰) were not significantly different between colonies (Student's  $t$  test,  $t_{33} = 0.19$ ,  $p = 0.854$ ), but  $\delta^{13}\text{C}$  (Hakluyt mean =  $-21.3$ ‰, Crimson Cliffs mean =  $-21.6$ ‰) was significantly different (Student's  $t$  test,  $t_{33} = 3.30$ ,  $p = 0.002$ ). These observations suggest that Dovekies in both colonies feed at a similar trophic level and foraging location (despite the statistically significant difference, the numeric difference in  $\delta^{13}\text{C}$  is minimal). GPS tracking of adults at a high Arctic colony in Svalbard (80° N, 11° E) showed individuals feeding up to 110 km from their colony (Jakubas et al. 2012). Although the distance between Hakluyt Island and Crimson Cliffs is 201 km, it is probable that when adults are feeding at the maximum distance from their breeding colonies, some overlap does occur, thus helping to explain the lack of temporal and spatial differences in Hg.

**Thick-billed Murres** Thick-billed Murres were sampled in 2010 and 2011 at Hakluyt Island, Saunders Island, and Parker Snow Bay. Thick-billed Murres sampled near Parker Snow Bay in 2010 (mean =  $770.2 \text{ ng g}^{-1}$ ,  $n = 18$ ) were significantly higher in Hg than those sampled at Saunders Island (Student's  $t$  test,  $t_{25} = 3.03$ ,  $p = 0.006$ ; mean =  $610.0 \text{ ng g}^{-1}$ ,  $n = 17$ ), and in 2011 murres at Hakluyt Island (mean =  $934.8 \text{ ng g}^{-1}$ ,

$n = 14$ ) were significantly higher in Hg than those sampled near Parker Snow Bay (Student's  $t$  test,  $t_{21} = 3.67$ ,  $p = 0.001$ ; mean =  $620.49 \text{ ng g}^{-1}$ ,  $n = 10$ ). Thick-billed Murres sampled in 2010 and 2011 near Parker Snow Bay showed a slightly significant (Student's  $t$  test,  $t_{26} = 2.03$ ,  $p = 0.053$ ) Hg difference (mean =  $770.2 \text{ ng g}^{-1}$ ,  $n = 18$ ; mean =  $620.5$ ,  $n = 10$ ; respectively). To help explain these Hg patterns, we looked at corresponding stable isotope samples. Few inter-annual isotopic patterns emerged for Thick-Billed Murres (due to lack of comparable samples in the same year), but both  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  were significantly different between the Parker Snow Bay and Hakluyt Island colonies in 2011 (more enriched at Hakluyt Island) (Online Resource 4).  $\delta^{15}\text{N}$  also differed significantly between Saunders Island and Parker Snow Bay in 2010 (Online Resource 4).

Spatial variation in Hg levels between murre colonies may result from differences in foraging areas and foraging behaviors. Information on foraging areas for adult Thick-billed Murres are available only for two of the colonies sampled in this study; Hakluyt Island and Saunders Island. Studies by Falk et al. (2001) and Frederiksen et al. (2017) show that individuals from each colony feed in distinctly different areas (primarily near their respective colonies) and no overlap in foraging areas is shown. A study at Hakluyt Island in 1997 and 1998 also showed variation in feeding depth of Thick-billed Murres, with murres feeding at significantly deeper depths in 1998 than in 1997 (Falk et al. 2002). Additional studies at Thick-billed Murre colonies by Gaston and Bradstreet (1993) in northeast Canada also showed considerable annual variation in prey consumed between colonies (although colonies were spaced slightly farther apart than our studied colonies) while Kokubun et al. (2010) showed inter-annual variation in prey consumed and foraging depth at a colony in Alaska, USA.

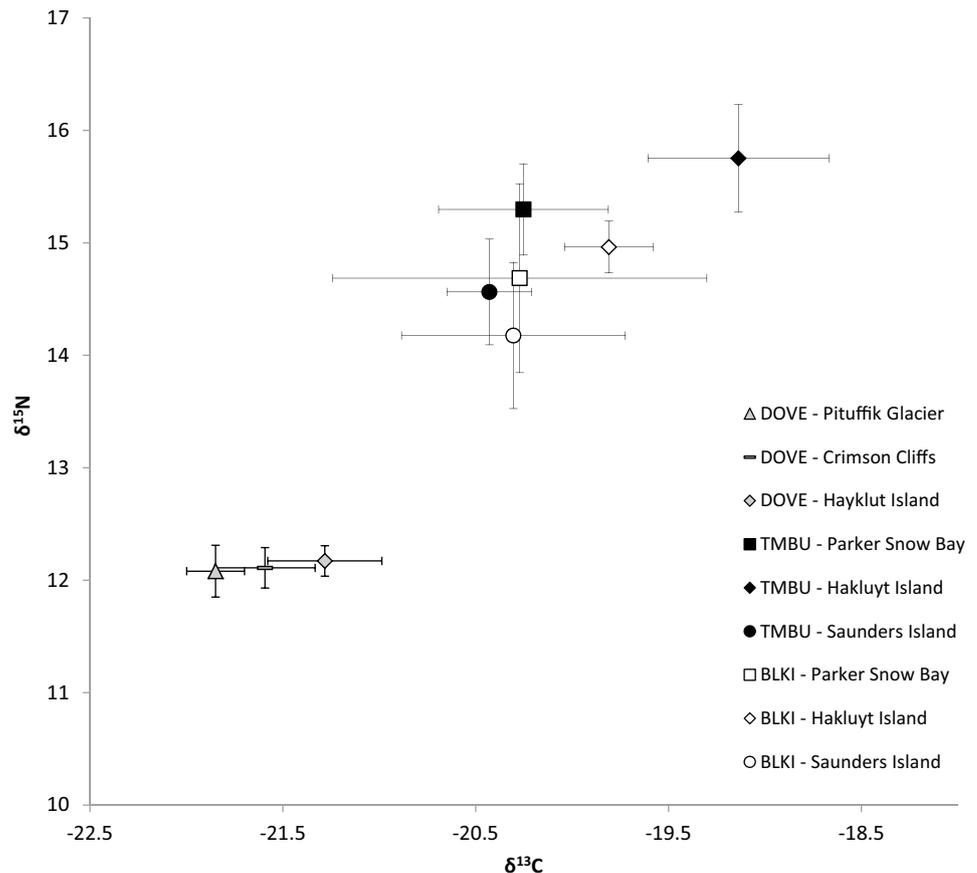
The reported foraging distances for Thick-billed Murres, Black-legged Kittiwakes, and Dovekies partially explains the observed Hg variation between colonies. Species with shorter foraging ranges (i.e., Thick-billed Murres and Black-legged Kittiwakes) showed significant difference in Hg concentration between colonies while species with much greater foraging ranges (i.e., Dovekies) lacked difference in Hg between colonies. Prey availability and diet varies seasonally in these species though (Harding et al. 2008; Karnovsky et al. 2008), so caution is warranted in using single season samples to draw large conclusions.

Although isotopic patterns in Dovekie and Thick-billed Murres were not as consistently statistically significant as Black-legged Kittiwakes, a visual plotting of combined 2010 and 2011 data for all three seabird species revealed a surprising pattern (Fig. 6). Samples from the central part of the study area (Saunders Island and west of Pituffik Glacier) are *all* isotopically more depleted in  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  than either the northern (Hakluyt Island) or southern

(Parker Snow Bay) sampling sites. Recall that Black-legged Kittiwakes on Saunders also exhibited  $\delta^{15}\text{N}$  values that decreased between 2010 and 2011. These points suggest that all three species in the central part of the study area are consuming prey species that are more freshwater tolerant (Causey et al. 2013). While it is well established that freshwater inputs are increasing across Arctic waters in the 21st century (Dyurgerov et al. 2010; Wassmann 2011), our isotopic results suggest this might not be occurring uniformly across our study area. The reason for this could be that the land surrounding Saunders Island on three sides contains more numerous freshwater outlets than any other portion of the study area (draining from permafrost and snowpack melt, and the Greenland Ice Sheet). Three major glaciers empty directly into Wolstenholme Fjord, several glaciers empty into Granville Fjord, three large rivers on the Thule Air Base peninsula drain west into North Star Bay, several drainages south of Thule Air Base empty into Baffin Bay, and Pituffik Glacier drains into Baffin Bay (Fig. 1). Discharge monitoring of one of these westward flowing rivers (Csank et al. 2011; Causey et al. 2013) shows an increasing trend in discharge (2010–2012), suggesting that a larger pulse of freshwater is altering and possibly shifting the prey availability in the central region towards more freshwater tolerant species. An anomalously large rain event (258 mm in 24 h) recorded at Thule Air Base on June 7, 2011 and above average June ( $3.49 \text{ }^\circ\text{C}$ ) and July ( $8.67 \text{ }^\circ\text{C}$ ) mean monthly temperature (NOAA 2016) may also have played a role in increasing freshwater inputs to the central portion of the study area.

These data suggest that significantly lower Hg levels for Black-legged Kittiwakes on Saunders Island and Thick-billed Murres on Saunders Island and Parker Snow Bay may be explained by differences in prey availability. Although we have a limited temporal data set, it appears that these species have not shifted their foraging habitat (evidenced by similar  $\delta^{13}\text{C}$  values), but are feeding spatially and temporally at lower trophic levels (as evidenced by declining  $\delta^{15}\text{N}$  values). Consuming more freshwater tolerant prey may thus be contributing to lower Hg concentrations. Braune et al. (Braune et al. 2014a, 2014b) also noted shifts in diet and temporal Hg trend changes for Thick-billed Murres (eggs) in two Canadian colonies, while Provencher et al. (2012) demonstrated the effects rapidly changing climatic conditions have on prey availability of Thick-billed Murres in the eastern Canadian Arctic. Emerging research suggests that  $\delta^{34}\text{S}$  may be an even greater predictor of Hg load in birds than  $\delta^{15}\text{N}$  or trophic position (Ramos et al. 2013; Elliot and Elliot 2016). Strong correlations between  $\delta^{34}\text{S}$  and Hg suggest that the amount of sulfate-reducing bacteria at the base of the aquatic food chain is critical in understanding where birds forage in an aquatic ecosystem (Elliot and Elliot 2016), thus providing insight to sources of Hg acquisition. We suggest

**Fig. 6** Stable isotope plot combining 2010 and 2011 samples from geographically distinct breeding colonies of three species (Black-legged Kittiwake, Thick-billed Murre, and Dovekie). > 5 adult samples were obtained for each species and colony. Four letter species codes defined in Table 1



that measurements of  $\delta^{34}\text{S}$  be included in future studies of avian blood Hg in the Arctic.

## Conclusion

Our study provides the first avian blood Hg results in the post-egg-laying season for northwest Greenland, and is a comprehensive study of spatial and temporal Hg and isotope patterns in the region. Mercury levels were positively correlated with  $\delta^{15}\text{N}$  levels in adults and juveniles, following an expected pattern of increasing Hg concentration with the increasing trophic level. Based on toxicity thresholds from Ackerman et al. (2016), 11 of our sampled species are at low risk for Hg toxicity, and Peregrine Falcon, Thick-billed Murre, and Black Guillemot are at moderate risk. However, research has shown that some avian species are more sensitive to MeHg toxicity than others (Heinz et al. 2009); thus, additional monitoring of the studied low- and moderate-risk species is warranted. Particular attention should be given to avian species which are either declining in number and/or are listed as “vulnerable” or “near threatened” on the *Greenland’s Red List—2007* (Boertmann 2007). Analyses of stable isotopes in

the blood of three abundant seabird species suggest that increased freshwater input into the central portion of the study area may be shifting available prey abundance to more freshwater-tolerant species and decreasing local acquisition of Hg compared to the same species at colonies in the northern and southern portion of the study area. Future studies are recommended to monitor changes in blood Hg and stable isotopes over longer time periods in this high Arctic region continually impacted by magnifying climatic change.

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## Compliance with ethical standards

**Conflict of interests** The authors declare that they have no conflicts of interest.

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