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1 **Environmental and life-history factors influence inter-colony and multidimensional niche**  
2 **metrics of a breeding Arctic marine bird**

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27 **Keywords**

28 Stable isotopes; carbon-13; nitrogen-15; Hg; isotopic niche; climate change; common eider

29 **Abstract**

30 Human industrialization has resulted in rapid climate change, leading to wide-scale  
31 environmental shifts. These shifts modify food web dynamics by altering the abundance and  
32 distribution of primary producers (ice algae and phytoplankton), as well as animals at higher  
33 trophic levels. Methylmercury (MeHg) is a neuro-endocrine disrupting compound which  
34 biomagnifies in animals as a function of prey choice, and, as such, bioavailability is affected by  
35 altered food web dynamics and adds an important risk-based dimension in studies of foraging  
36 ecology. We determined the multidimensional ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , THg) niche dynamics (MDND)  
37 among breeding common eider (*Somateria mollissima*) ducks sampled from 10 breeding  
38 colonies distributed across the circumpolar Arctic and subarctic. Results show high variation in  
39 MDND among colonies as indicated by niche size and ranges in  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and THg values in  
40 relation to spatial differences in primary production inferred from sea-ice presence and colony  
41 migratory status. Colonies with higher sea-ice cover during the pre-incubation period had higher  
42 median colony THg,  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ . Individuals at migratory colonies had relatively higher THg  
43 and  $\delta^{15}\text{N}$  and lower  $\delta^{13}\text{C}$ , suggesting a higher trophic position and a greater reliance on  
44 phytoplankton-based prey. We conclude that variation in MDND exists amongst eider colonies  
45 which influenced individual blood THg concentrations. Further exploration of spatial  
46 ecotoxicology and niche characteristics at each individual site is important to examine the  
47 relationships between anthropogenic activities, foraging behaviour, and the related risks of  
48 contaminant exposure. Multidimensional niche analysis that incorporates multiple isotopic  
49 and contaminant metrics could help identify those populations at risk to rapidly altered food  
50 web dynamics, notably important to the Indigenous populations that rely on eiders as a  
51 stable resource.

52 **Highlights**

- 53 1. Common eider colonies vary in their multidimensional ( $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$ , THg) niche size.  
54 2. Colonies with higher sea-ice cover had higher  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$  and THg.  
55 3. Colonies considered migratory had higher average  $\delta^{15}\text{N}$  and THg, but lower  $\delta^{13}\text{C}$ .  
56 4. Individuals with lower  $\delta^{13}\text{C}$  and higher trophic positions had higher THg.

57

58 **Graphical Abstract**



**Migratory Colonies**    **↑ Sea Ice Cover**



↑  $\delta^{15}\text{N}$   
↑ THg  
↓  $\delta^{13}\text{C}$



↑  $\delta^{15}\text{N}$   
↑ THg  
↑  $\delta^{13}\text{C}$

59

60 **1. Introduction**

61 Global anthropogenic activity has resulted in environmental shifts within Arctic systems  
62 including rising air and ocean temperatures (Zhang 2005; Screen and Simmonds 2010; Najafi et  
63 al. 2015), changes in wind and ocean circulation (Timmermans et al. 2011), a dramatic  
64 modification of sea-ice cover in polar marine systems (Johannessen et al. 2004; Hoegh-Guldberg  
65 and Bruno 2010; IPCC 2019), and an elevated transport and deposition of biologically harmful  
66 contaminants (Dietz et al. 2009; Liu et al. 2012; Foster et al. 2019). These multiple stressors  
67 generate cumulative effects which have direct and indirect influences on biological systems,  
68 ultimately having the potential to affect food web characteristics including prey availability and  
69 selection (Vasseur and McCann 2005; Frederiksen et al. 2006; Parmesan 2006). Arctic marine  
70 food-webs have been particularly impacted, leading to dramatic abiotic shifts resulting in  
71 alterations of prey abundance and availability which have modified the foraging niche of higher  
72 trophic-level organisms (Moline et al. 2008; Pecuchet et al. 2020).

73 The foraging niche of an organism includes both dietary and environmental components,  
74 and therefore has been used to discern both trophic roles by consumers and changes in their  
75 resource use (Newsome et al. 2007). Studies examining foraging niche size (the spatial and  
76 trophic-level range at which a group forages) have been used to investigate the effect of  
77 phenological changes in primary production on predators (Rabosky 2009). In polar regions,  
78 changes in the abundance, distribution, and phenology of primary producers such as  
79 phytoplankton and sea ice-algae can have effects on higher trophic-level wildlife (Frederiksen et  
80 al. 2006; Kohlbach et al. 2016; Renaut et al. 2018; Lewis et al. 2020). Sympagic-pelagic-benthic  
81 coupling drives energy flow between the surface and benthic habitats and provides a foundation  
82 for Arctic ecosystem functioning involving benthic consumers but is being decoupled due to

83 changing sea-ice dynamics (Søreide et al. 2012; Kohlbach et al. 2016; Yurkowski et al. 2020a).  
84 These shifts can generate bottom-up effects on the foraging ecology of higher trophic species,  
85 especially those that rely on consuming resources that inhabit the sea floor (Leu et al. 2011; Post  
86 et al. 2013; Post 2017; Cusset et al. 2019).

87 Stable isotopes of carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) are tracers that provide time-  
88 integrated information on habitat use and diet (Bearhop et al. 2006; Cherel and Hobson 2007;  
89 Inger and Bearhop 2008). In coastal polar environments,  $\delta^{13}\text{C}$  provides dietary information on  
90 sources of primary productivity and foraging habitat, for example, between  $^{13}\text{C}$ -depleted  
91 phytoplankton-derived carbon and  $^{13}\text{C}$ -enriched sea-ice derived carbon (Hobson et al. 2002;  
92 Kohlbach et al. 2016; Yurkowski et al. 2020a; Lewis et al. 2020). In addition, benthic or  
93 nearshore environments are typically enriched in  $^{13}\text{C}$  compared to pelagic or offshore sources  
94 (Hobson and Welch 1992; Hobson et al. 1995; France 1995). Values of  $\delta^{15}\text{N}$  indicate relative  
95 trophic level, with higher trophic levels associated with increased  $\delta^{15}\text{N}$  values (Hobson and  
96 Welch 1992).

97 One further consequence of changing Arctic marine ecosystems is shifts in marine  
98 wildlife exposure to contaminants (Muir et al. 1999; Macdonald et al. 2005; Stern et al. 2012). It  
99 is well established that Arctic marine food webs are influenced by long-range transport of  
100 contaminants (Macdonald et al. 2000; Braune et al. 2005; Kirk et al. 2012). On top of this, the  
101 melting of permafrost, ice caps and glaciers is releasing stored contaminants from years of higher  
102 contaminant output into the current system (Rydberg et al. 2010; Schuster et al. 2018).  
103 Methylmercury (MeHg) is a biologically converted form of mercury (Hg) and is a contaminant  
104 of concern due to its high bioavailability in organic tissues and toxic effects at even low, sub-  
105 lethal concentrations (Wiener et al. 2003; Whitney and Cristol 2017; Evers 2018). Uptake of

106 MeHg into wildlife can disrupt endocrine functioning, behaviour, and reproductive success  
107 (Cardona-Marek et al. 2009; Chen and Hale 2010; Whitney and Cristol 2017). Specifically,  
108 reproductive effects in birds include reduced clutch size, altered parental breeding behaviour and  
109 reduced hatching and fledgling success (Braune et al. 2012; Tartu et al. 2013; Goutte et al. 2014;  
110 Hartman et al. 2019). Together, these impacts may result in slowed or negative population  
111 growth rates and reproductive success in individuals exposed as juveniles (Schoch et al. 2014;  
112 Paris et al. 2018).

113       Climate change and human activity in Arctic ecosystems affect the distribution and  
114 accumulation of Hg (Stern et al. 2012; McKinney et al. 2015). Further, changes in Arctic food  
115 web dynamics and trophic relationships may shift the flow of Hg between organisms (Braune et  
116 al. 2014). To study this,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  measurements are tools that help determine  
117 environmental and dietary sources of Hg due to varying Hg uptake with carbon-source use and  
118 trophic level (Atwell et al. 1998; Cardona-Marek et al. 2009; Pomerleau et al. 2016). While  $\delta^{15}\text{N}$   
119 indicates trophic level, with greater Hg concentrations through food web biomagnification, high  
120 variability in Hg still occurs among individuals despite similar  $\delta^{15}\text{N}$  values (Atwell et al. 1998;  
121 Bearhop et al. 2000; DiMento et al. 2019). Furthermore, isotope biplots consisting of just  $\delta^{13}\text{C}$   
122 and  $\delta^{15}\text{N}$  obviously capture an incomplete portrayal of ecological niche due to the inclusion of  
123 only two isotopic variables. A multidimensional niche, including three or more total variables,  
124 can provide more information to assess foraging ecology (Swanson et al. 2015, Hobson et al.  
125 2015, O'Donovan et al. 2018). Therefore, including Hg in niche analyses along with  $\delta^{13}\text{C}$  and  
126  $\delta^{15}\text{N}$  provides a broader method to quantify an individual and population's foraging ecology and  
127 multidimensional niche dynamics (Yurkowski et al. 2020b). This analytical approach, combining  
128 stable isotopes and contaminants has been applied to multiple taxa including mammals, fish, and

129 reptiles (Guzzo et al. 2016; Jackson et al. 2016; Purwandana et al. 2016; Yurkowski et al.  
130 2020b). However, a multidimensional approach to determine niche size has not been investigated  
131 in seabirds despite them being considered sentinels of ecosystem change (Le Bohec et al. 2013).  
132 Arctic seabirds demonstrate varying foraging specializations on a large diversity of prey items  
133 reflecting climate-induced trophic shifts and inform spatial variation and temporal changes in  
134 sea-ice and ocean dynamics that propagate up the food web, making them an ideal model to  
135 research multidimensional niche dynamics (Pratte et al. 2019; Albert et al. 2020; Renedo et al.  
136 2020).

137         We used an inter-colony and inter-individual approach to examine spatial variation in the  
138 3-dimensional niche of common eiders (*Somateria mollissima*, hereafter eiders). Eiders are a  
139 long-lived, colonial-nesting marine bird with high site fidelity and widely dispersed breeding  
140 populations across the circumpolar Arctic. Across their range, eiders are likely exposed to  
141 diverse environmental conditions that influence colony demographics at varying intensities that  
142 may influence foraging decisions and, although typically at low concentrations in eiders, Hg  
143 exposure (Mallory et al. 2004; 2017; Jónsson et al. 2013; Goudie et al. 2020; Noel et al. 2021).  
144 Eider prey primarily includes a diversity of benthic invertebrates (e.g., urchins, mussels, and  
145 gastropods) as well as pelagic macroinvertebrates to a lesser extent (e.g., amphipods; Sénéchal et  
146 al. 2011; Kristjánsson et al. 2013; Waltho and Coulson 2015). The abundance and distribution of  
147 these prey groups vary spatio-temporally and correlate with both predator Hg concentrations and  
148 phenological shifts in primary production (Mouritsen et al. 2005; Barber et al. 2015; Fort et al.  
149 2016; Savoy et al. 2017). Thus, examining  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$  and Hg niche dynamics of a costal,  
150 primarily benthic foraging species provides an avenue to investigate the future impact of prey  
151 shifts and the resulting influence on Hg exposure (Sénéchal et al. 2011), as well as relative



152 differences in ice algae and phytoplankton-based food webs in relation to sea-ice cover (Søreide  
153 et al. 2012; Kohlbach et al. 2016).

154         We used a 3-dimensional approach combining  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$  and total Hg (THg)  
155 measurements collected from individuals at 10 eider breeding colonies located across their  
156 circumpolar range to evaluate variation in eider foraging ecology and Hg exposure. We  
157 anticipated that colonies would show differences in 3-dimensional niche size and ranges of each  
158 axis and be influenced by spatial differences in primary productivity (i.e., sea-ice algae and  
159 phytoplankton) and migratory behaviour. To examine these possible drivers of colony-level  
160 variation in niche metrics, we first examined colony sea-ice cover during a period reflecting  
161 periods of isotopic integration in blood. Specifically, we predicted that colonies with higher sea-  
162 ice cover would have smaller niche sizes than those with no sea ice present due to more  
163 restricted foraging habitat and likely less diverse prey availability (Yurkowski et al. 2016; Pratte  
164 et al. 2019). We also examined whether a colony is considered primarily migratory or resident  
165 and predicted that eiders from resident, non-migratory colonies would have smaller niche sizes  
166 compared to migratory colonies, given that residents remain at the same geographical location  
167 year-round and should therefore be continually exposed to a narrower range of environmental  
168 conditions than migrants (Herrera 1978; Gómez et al. 2016).

169         In our second objective, as colony-corrected individual values and colony ranges of  $\delta^{13}\text{C}$ ,  
170  $\delta^{15}\text{N}$  and THg provide important and unique information about foraging ecology, we first related  
171 these values to colony sea-ice cover in the spring during the period when birds would have been  
172 foraging at high rates to obtain body condition needed to breed. We predicted that colonies with  
173 higher sea-ice cover during the pre-breeding period would have lower  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and THg ranges  
174 due to a restricted number of foraging locations available due to higher sea-ice concentrations, as

175 well as higher individual  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and THg. Second, we related these metrics to the migratory  
176 status of a colony. We predicted that migratory colonies would have wider  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and THg  
177 ranges due to a presumed broader distribution and use of habitat, in addition to higher median  
178 THg,  $\delta^{15}\text{N}$  and lower  $\delta^{13}\text{C}$ . Median values were used to avoid data skewed by high/low  
179 individual values within a mean and better represent general colony values.

180 Finally, we aimed to assess individual Hg exposure based on possible differences in  
181 foraging behaviour and prey selection. We examined the relationship between trophic position  
182 (the vertical placement of an individual in the food-web based on prey and individual  $\delta^{15}\text{N}$ ) and  
183 inter-individual  $\delta^{13}\text{C}$  values on THg concentrations. We predicted that THg would increase with  
184 higher trophic position due to the biomagnification of THg, and lower  $\delta^{13}\text{C}$  values because of a  
185 greater consumption of resources derived from phytoplankton (Atwell et al. 1998; McMahon et  
186 al. 2006; Stern et al. 2012). By examining variation in 3-dimensional niche size among colonies  
187 of this Arctic seabird, we aimed to identify the environmental and behavioural factors  
188 influencing niche dynamics. Furthermore, multidimensional niche can be used to infer  
189 population-level variability in resource use and overall niche diversity which allows for broad  
190 predictions about predicted flexibility and resiliency to environmental change (Vander Zanden et  
191 al. 2010; Paredes et al. 2012; Smith and Reeves 2012; Sydeman et al. 2012). As such, we also  
192 considered how our measurement of niche size may help predict the resiliency of eider colonies  
193 to environmental change (Paredes et al. 2012; Smith and Reeves 2012; Sydeman et al. 2012).

## 194 **2. Methods**

### 195 ***2.1. Study sites and sample collection***

196 We collected whole blood samples from pre-incubating or incubating eiders in 2018 at 10  
197 breeding colonies (total number of individuals = 240) across the Arctic and subarctic (spanning a

198 longitude from -147.776 to 35.774 and latitude from 78.918 to 43.645; Figure 1, Table 1). We  
199 captured eiders using colony- and breeding stage-specific techniques. Pre-incubating eiders were  
200 sampled at East Bay Island (within in the Qaqsauqtuuq (East Bay) Migratory Bird Sanctuary,  
201 Nunavut, Canada), whereas incubating eiders were sampled at the other nine locations.

202         At East Bay Island, eiders were captured using large flight nets. We collected birds from  
203 the nets and drew a 1-mL tarsal blood sample from each female eider (Hennin et al. 2015). These  
204 samples were used for isotopic analyses and were collected using a 23G thin-wall, 1-inch needle  
205 attached to a sodium-heparinized 1 mL syringe (Lemons et al. 2012). After transferring to a  
206 heparinized 1.5 mL Eppendorf tube, samples were kept cool (~10°C), and within 8 h, were  
207 centrifuged at 10,000 rpm for 10 min to separate red blood cells (RBCs) and plasma. Plasma was  
208 then transferred by pipetting into a separate cryovial and stored along with RBC samples at -  
209 20°C until isotopic analysis. During the same capture period as the first sample, a second blood  
210 sample of 1-mL was obtained from the jugular vein using 23G thin wall, 1-inch needles attached  
211 to heparinized 3mL syringes to be used for Hg analysis. The whole blood sample was placed in  
212 acid-rinsed cryovials and kept at ~10°C, and frozen within 6 hours of collection until analysis.

213         At the other nine colonies, female eiders were captured on their nest during incubation  
214 using either a bownet, noose pole or dogs (John's Island location only; Milton et al. 2016). The  
215 specific incubation stage could not be determined at all sites or for all individuals and was  
216 excluded from analysis. For most sites, we collected 200-1000 µL of blood from the tarsal vein  
217 using a 23G thin-wall, 1-inch needle attached to a heparinized 1 mL syringe. At the Alaskan site,  
218 up to 5mL of blood was collected from the jugular vein using a non-heparinized syringe, while at  
219 the Icelandic site, blood was collected from the brachial vein. After collection, samples were  
220 kept cool and transferred to heparinized 1.5mL cryovials. Within 8-12 h, samples were

221 centrifuged at approximately 10,000 rpm, dependent on centrifuge model, for 10 min to separate  
222 red blood cells (RBCs) and plasma. Plasma was then placed into a separate cryovial and stored  
223 along with RBC samples at a minimum of -20°C until analysis.

## 224 **2.2. Stable isotope analysis**

225 Stable isotopes of elements turnover at different rates based on dietary composition, metabolic  
226 rates, and specific metabolic activity of the tissue (Hobson and Clark 1992). Isotopic half-life is  
227 dependent on body size and can be affected by temperature exposure (Carleton and Del Rio  
228 2005). For avian blood components, plasma has fast turnover rate that reflects recent diet (days),  
229 while the turnover rate of RBCs is slower and reflects diet over a longer period (weeks; Hobson  
230 and Clark 1992; Barquete et al. 2013). Further,  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  usually have similar turnover  
231 times, hence are comparable (Bearhop et al. 2002). Stable isotope ratios were measured in  
232 plasma at East Bay Island and in RBCs at the other nine colonies. Therefore, despite sampling  
233 colonies at different life history stages, by using different tissues for analysis we were still able  
234 to compare them within a similar stage including the pre-incubation period while eiders are  
235 heavily foraging, either at resident sites or in the last period of migration to build up stored  
236 resources for their incubation fast.

237 Samples were freeze-dried for approximately 72 h after collection. Samples were then  
238 ground into a fine, homogenized powder using a metal spatula cleaned with acetone. Plasma  
239 samples were then lipid extracted using a 2:1 chloroform:methanol solution (Søreide et al. 2006).  
240 Specifically, 2:1 chloroform:methanol solution (1.9mL) was added to 100 $\mu\text{L}$  of each plasma  
241 sample, which were then placed in a water bath at 30°C for 24 h. Samples were then centrifuged  
242 at 15,000 rpm for 10 min to separate the lipid solution from the plasma pellet. A p1000 pipette  
243 was used to remove the lipid solution, leaving the plasma pellet behind. The pellet was washed

244 again with an additional 1.9 mL of the chloroform:methanol solution and centrifuged for a final  
245 10 min at 15,000 rpm. The remaining lipid solution was removed, leaving only a plasma pellet.  
246 Samples were left open in the fume hood for 24 h to allow for any remaining  
247 chloroform:methanol solution to evaporate. Since RBCs have minimal lipids present, they did  
248 not undergo lipid extraction (Hobson and Clark 1992).

249 Plasma and RBC samples were weighed into individual tin-capsules using a 4-digit  
250 balance to obtain 0.3-0.5 mg of sample. Plasma samples were prepared at the University of  
251 Windsor, and plasma stable isotopes were analysed at the Environment and Climate Change  
252 Canada Stable Isotope Laboratory in Saskatoon, Saskatchewan, using continuous-flow isotope-  
253 ratio mass spectrometry (CFIRMS; Harris et al. 1997). Samples were weighed into pre-  
254 combusted tin capsules. Encapsulated plasma was combusted at 1030°C in a Carlo Erba NA1500  
255 or Eurovector 3000 elemental analyser. The resulting N<sub>2</sub> and CO<sub>2</sub> were separated  
256 chromatographically and introduced to an Elementar Isoprime or a Nu Instruments Horizon  
257 isotope ratio mass spectrometer. Two reference materials were used to normalize the results to  
258 VPDB and AIR: BWBIII keratin ( $\delta^{13}\text{C} = -20.18$ ,  $\delta^{15}\text{N} = +14.31$  ‰, respectively) and PRCgel  
259 ( $\delta^{13}\text{C} = -13.64$ ,  $\delta^{15}\text{N} = +5.07$  ‰, respectively). Within run (n = 5) precisions as determined from  
260 both reference and sample duplicate analyses were  $\pm 0.1$  ‰ for both  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ .

261 The RBC samples were prepared for isotope analysis at La Rochelle University, France,  
262 and were analysed at the LIENSs institute (La Rochelle, France) as detailed in Fort et al. (2014).  
263 Plasma and RBC samples were combusted using a Eurovector 3000 (Milan, Italy) elemental  
264 analyser which results in production of N<sub>2</sub> and CO<sub>2</sub> gases. These were separated by gas  
265 chromatography and introduced into a NU Horizon (Nu Instruments, Wrexham, UK) triple-  
266 collector isotope-ratio mass-spectrometer via an open split. Ratios of carbon ( $^{13}\text{C}/^{12}\text{C}$ ) and

267 nitrogen ( $^{15}\text{N}/^{14}\text{N}$ ) were expressed in typical delta notation ( $\delta$ ) as per mil (‰) deviation from the  
268 primary standards (Vienna Pee Dee Belemnite (VDPB) and atmospheric nitrogen (AIR),  
269 respectively). Replicate measurements ( $n = 20$ ) per run of laboratory standards (USGS-61 and  
270 USGS-62) indicated that the measurement accuracy was  $<0.2\text{‰}$  for both  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  values.  
271 Blanks were run at the beginning of each sample set. Detection limit was set to  $0.005 \mu\text{g/g dw}$ .

272         Due to biogeochemical factors, baseline stable isotopes of Arctic marine food webs vary  
273 spatiotemporally (de la Vega et al. 2019). Variation in food web  $\delta^{13}\text{C}$  of marine environments is  
274 driven largely by primary production growth rate and inorganic substrate (e.g., water  
275 temperature, amount and isotopic signature of dissolved  $\text{CO}_2$ )  $\delta^{13}\text{C}$  and these, in turn, can be  
276 influenced by sea-ice cover (de la Vega et al. 2019). Stable nitrogen isotope values in marine  
277 food webs are influenced by spatial and temporal changes in temperature, increasing abundance  
278 of phytoplankton that fix  $^{15}\text{N}$ , trophic level as well as inputs of nitrogen from terrestrial sources  
279 (Smith et al. 1999; Tamelander et al. 2009; McMahon et al. 2013). Importantly, since Arctic food  
280 webs are expected to vary isotopically, measured  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of biota from different  
281 regions can only be compared if corrected for such baseline variance (Bowen 2010; Hobson et al.  
282 2012; de la Vega et al. 2019). Based on previously published  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of known  
283 eider bivalve prey at the different breeding sites, we corrected our data by subtracting baseline  
284 bivalve isotope values from the eider tissue values to obtain “corrected” isotopic values (Table  
285 2). However, Hg values were not corrected to baseline values. Additionally, we were unable to  
286 account for the potential impact of incubation stage on  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$  or Hg values. Both Hg and  
287  $\delta^{15}\text{N}$  values can be elevated in blood due to mobilization of internal nutrient stores during the  
288 incubation fast (Hobson et al. 1993; Wayland et al. 2005). However, our use of RBCs instead of  
289 plasma to determine incubating female  $\delta^{15}\text{N}$  values minimized this effect (Cherel et al. 2005).

290 Furthermore, our sampling of eiders during incubation, when Hg is known to increase (Wayland  
291 et al. 2005), lessens but does not mitigate the potential bias of East Bay Island pre-breeding  
292 eiders having elevated Hg relative to the other colonies as the pre-breeding eiders have not yet  
293 depurated Hg to their eggs during laying (Akearok et al. 2010). Hence, caution should be taken  
294 when comparing Hg values between East Bay Island and the other nine colonies.

295 Diet-tissue isotopic discrimination factors allow modeling of isotopic trophic positions or  
296 nutrient source tracing (e.g., Wolf et al. 2009; Federer et al. 2010; Bond and Diamond 2011).  
297 Such factors have not been established for common eiders and so we used those reported by  
298 Federer et al. (2010) for spectacled eider (*Somateria fischeri*) (plasma: +4.9‰; RBC: +4.0‰).  
299 Trophic position was calculated using baseline  $\delta^{15}\text{N}$  bivalve values for the individual's colony  
300 ( $\delta^{15}\text{N}_{\text{base}}$ ), discrimination factors from the respective tissue of spectacled eiders ( $\delta^{15}\text{N}_{\text{TDF}}$ ; Federer  
301 et al. 2010), trophic position (TP) of baseline prey values ( $\text{TP}_{\text{base}}$ ; value of 2 consistent with eider  
302 prey), and the non-colony corrected  $\delta^{15}\text{N}$  values for that individual eider ( $\delta^{15}\text{N}_{\text{eider}}$ ; Hobson and  
303 Welch 1992; Vander Zanden et al. 1997; Vander Zanden and Rasmussen 1999).

304 
$$\text{TP} = ((\delta^{15}\text{N}_{\text{eider}} - \delta^{15}\text{N}_{\text{base}}) / \delta^{15}\text{N}_{\text{TDF}}) + \text{TP}_{\text{base}}$$

### 305 **2.3. THg analysis**

306 Whole blood collected at East Bay Island was sent to the Research and Productivity Council  
307 (RPC) in New Brunswick, Canada for THg analysis. Each sample was prepared by microwave-  
308 assisted digestion in nitric acid (SOP 4.M26). Mercury was then analysed by cold vapour atomic  
309 absorption spectroscopy (AAS; SOP 4.M52 & SOP 4.M53) to obtain THg concentrations.  
310 Quality assurance/control procedures included analysis of four reagent blanks, and reference  
311 materials from dogfish liver (DOLT-2) and lobster hepatopancreas (TORT-2) from the National

312 Research Council (NRC), Canada, as well as four randomly selected duplicate samples. All  
313 samples followed quality control procedures. Mercury concentrations were converted from wet  
314 weight to dry weight for comparison with the other colonies following known equations and  
315 moisture values for avian blood at 79% (Eagles-Smith et al. 2008).

316 For the remaining nine colonies, THg analyses were conducted at LIENSs Institute using  
317 RBCs separated from plasma collected from incubating females. These eiders were captured  
318 while incubating (Hanssen et al. 2002; Bottitta et al. 2003; Sénéchal et al. 2011), thus by  
319 collecting and analysing RBCs alone, the timeframe which the RBCs represent aligns with the  
320 same timeframe represented in the East Bay Island eiders (pre-incubation period for all colonies)  
321 since whole blood has a turnover rate approximately intermediate of plasma and RBC (Cherel et  
322 al. 2005). Therefore, this provides justification for including the colony in our analysis despite  
323 potential differences in physiology due to their reproductive stages. Freeze-dried blood was  
324 analysed using an Advanced Hg Analyser spectrophotometer (Altec AMA 254). A quality  
325 control program included running blanks prior to the analysis, as well as the same certified  
326 reference materials used to analyze the samples from East Bay Island (DOLT-2 and TORT-2)  
327 analysed every 15 samples. Samples were analyzed for THg since Hg exists as primarily MeHg  
328 in avian blood (near 1:1 ratio; Wiener et al. 2003; Rimmer et al. 2005).

#### 329 **2.4. Statistical analysis**

330 We estimated 3-dimensional niche size (using THg,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) and ranges along the THg,  
331  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  axes for 10 eider colonies using the R package nicheROVER v1.0 (Swanson et al.  
332 2015) in R version 3.6.2 (R Development Core Team). NicheROVER uses Bayesian statistical  
333 methods to calculate a multidimensional niche region in multivariate space that represents the  
334 spatial breadth and placement of a group's (i.e., colony's) niche in relation to other groups and



335 infers the niche size of each group based on the group's individual values (Swanson et al. 2015).  
336 Since the variables are in different units ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ : ‰ vs. THg:  $\mu\text{g/g}^{-1}$ ), we scaled and  
337 centred all values by subtracting the mean for each variable and dividing it by the standard  
338 deviation, thereby standardizing all data. To determine if there were any correlations among  
339 variables prior to analysis, we tested for independence by calculating Spearman's correlation  
340 coefficient between THg and colony-corrected  $\delta^{15}\text{N}$  which showed a significant but weak  
341 correlation ( $R=0.429$ ,  $p<0.001$ ). Thus, THg and  $\delta^{15}\text{N}$ , while related, do possess independent  
342 variation that allows us to use both in our analysis to account for spatial variation in THg  
343 concentrations. We calculated a 95% probability niche region in multivariate space at 10,000  
344 iterations using diffuse priors (Swanson et al. 2015; Yurkowski et al. 2020b). We ran additional  
345 script at 10,000 iterations to obtain  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and THg ranges (difference between the highest  
346 and lowest values; Swanson et al. 2015; Yurkowski et al. 2020b). Three-dimensional models of  
347 the niche ranges were visualized using the scatter3D function in the car package v.3.0-9 (Fox and  
348 Weisberg 2019) and the rgl package v.0.100.54 (Adler and Murdoch 2017; see Supplemental  
349 Materials).

350 Primary migratory status of each colony, not including the potential for individual  
351 variation, was determined by consulting previous studies (Schamel 1997; Bønløkke et al. 2006;  
352 Hanssen et al. 2016; Steenweg et al. 2017; Mallory et al. 2020) and through spatial tracking data  
353 collected by the SEATRACK program (<https://seapop.no/en/seatrack/>). Moreover, we  
354 determined the proportion of sea-ice cover surrounding each colony within a timeframe  
355 reflecting turnover rates of isotope sampling (plasma within a week of sampling, RBC within a  
356 month of sampling; Hobson and Clark 1992; Barquete et al. 2013). Sea-ice cover was determined  
357 via a satellite image of a 100 km area around each colony on a cloud-less day from NASA

358 Worldview dataset (EOSDIS, <https://worldview.earthdata.nasa.gov>). Land pixels were removed  
359 from the image manually and the remaining pixels were categorized into two groups (open water  
360 or sea ice) using a K-means clustering procedure via RGB values of the pixels  
361 (<http://mkweb.bcgsc.ca/color-summarizer/>). The resulting proportion of pixels was used as a  
362 proxy for the proportion of sea ice around the colony during the time of isotopic turnover for  
363 each colony (Cusset et al. 2019).

364 We ran a preliminary 2-tailed *t*-test to determine independence between colony sea-ice  
365 cover and migratory behaviour and found they were not significantly correlated ( $t_5=2.11$ ,  
366  $p=0.09$ ). Therefore, to determine sources of niche variation with sea ice cover, we first ran a  
367 general linear model (GLM) to determine how log-transformed niche size varied by colony sea  
368 ice cover. Next, we conducted six GLMs to analyze the relationship between sea-ice cover and  
369 colony  $\delta^{15}\text{N}$ , log-transformed  $\delta^{13}\text{C}$  and THg ranges, as well as median individual colony-  
370 corrected  $\delta^{15}\text{N}$ , and log-transformed  $\delta^{13}\text{C}$  and THg values for each of the 10 colonies.

371 To examine variation in niche dynamics between migratory and resident colonies we  
372 conducted a 2-tailed *t*-test to analyze how log-transformed colony niche size varied with  
373 migratory status (migratory or resident being the two groups). Following this, we ran six, 2-tailed  
374 *t*-tests to analyze whether migratory status of a colony resulted in different colony  $\delta^{15}\text{N}$ , and log-  
375 transformed  $\delta^{13}\text{C}$  and THg ranges, as well as individual colony-corrected eider  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and  
376 log-transformed THg values.

377 Finally, we used a general linear mixed model (GLMM) to examine the relationship  
378 between colony-corrected isotopes indicating carbon source ( $\delta^{13}\text{C}$ ), trophic position of each  
379 individual, and log-transformed THg. The model consisted of THg as the dependent variable,  
380 with  $\delta^{13}\text{C}$  and trophic position as independent variables, as well as colony as a random variable.

381 All models conducted throughout the study met statistical assumptions, and all log-  
382 transformations were conducted using natural log.

### 383 **3. Results**

#### 384 ***3.1. Niche size and underlying sources of variation***

385 Three-dimensional niche size was highly variable among colonies, ranging from 1.4 (Grindøya)  
386 to 21.7 (Iceland), with an average niche size among all colonies of  $9.2 \pm 7.8$  (Figure 2, see  
387 Supplemental Materials). However, niche size was not correlated with colony sea ice cover ( $t_s=-$   
388  $0.92$ ,  $p=0.54$ ) or migratory status ( $t_4=-0.61$ ,  $p=0.57$ ). The Christiansø colony in Denmark had the  
389 lowest colony-corrected  $\delta^{13}\text{C}$  values, suggesting higher phytoplankton-derived carbon in their  
390 diet, while the Alaskan colony had the highest colony-corrected  $\delta^{13}\text{C}$  suggesting eiders were  
391 feeding on prey reflecting more ice algae- or inshore-derived carbon (see Supplemental  
392 Materials). The Alaskan colony also had the highest colony-corrected  $\delta^{15}\text{N}$  values, with the  
393 Faroe Islands having the lowest values, suggesting that Faroese eiders forage at lower trophic  
394 levels, whereas the Alaskan eiders forage at higher trophic levels.

#### 395 ***3.2. Relationship between colony migratory behaviour and sea-ice cover with isotopes and*** 396 ***THg***

397 Inter-colony variation in sea-ice presence was positively correlated with median eider THg  
398 concentrations, as well as  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  values (Table 3). However,  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$  as well as THg  
399 ranges did not vary with colony sea-ice cover (Table 3). Migratory colonies had higher  
400 individual  $\delta^{15}\text{N}$  and THg, as well as lower individual  $\delta^{13}\text{C}$  compared to individuals captured at  
401 resident colonies (Table 3). However,  $\delta^{15}\text{N}$  range,  $\delta^{13}\text{C}$  range and THg range did not vary  
402 between the migratory and resident colonies (Table 3).

403 **3.3. Relationship between isotopic niche and THg concentrations**

404 Both colony-corrected  $\delta^{13}\text{C}$  and trophic position predicted THg concentration within individuals.  
405 Specifically, individuals with a lower  $\delta^{13}\text{C}$  value (phytoplankton-based foraging) had higher THg  
406 values (Table 3, Figure 3). Additionally, THg significantly increased with trophic position,  
407 where individuals with higher trophic positions had greater THg values (Table 3, Figure 3).

408 **4. Discussion**

409 Using data collected from ten eider colonies located throughout their circumpolar range,  
410 including both Arctic and subarctic sites, we quantified 3-dimensional niche size using  $\delta^{15}\text{N}$ ,  
411  $\delta^{13}\text{C}$  and THg to determine colony niche size and ranges. Determination of 3-dimensional niche  
412 size allowed us to broadly compare a snapshot of diet breadth at multiple eider colonies in  
413 relation to environmental and behavioural differences, as well as infer their potential for  
414 flexibility in response to environmental change. We demonstrate the benefits of using multiple  
415 chemical tracers when assessing the effects of spatial variation and environmental gradients on  
416 the foraging ecology of highly mobile consumers (Ramos and González-Solís 2012). This study  
417 represents the first inter-colony, multidimensional niche size analysis for any seabird and the  
418 resulting colony-level relationships with THg exposure, an area identified as a key knowledge  
419 gap (Dietz et al. 2019).

420 **4.1. Colony foraging flexibility and resiliency predictions**

421 Generally, colonies that utilize broader, more generalist diets are expected to have larger  
422 foraging niches, thus are expected to be inherently less vulnerable to changes since they have  
423 greater flexibility in their prey source as they forage on a wide variety of organisms and habitats  
424 (Jakubas et al. 2017; Both et al. 2010). Colonies with restricted, specialist diets are expected to  
425 have smaller foraging niches, influenced by both prey availability and foraging distance, and are

426 generally viewed as more vulnerable to environmental changes (Bolnick et al. 2003; Araújo et al.  
427 2011; Pratte et al. 2019). We examined the 3-dimensional niche size of eider breeding colonies,  
428 representing prey selection and trophic connections through stable isotopes and Hg exposure.  
429 Multidimensional niche analysis may be useful in predicting the resiliency of common eider  
430 colonies to ongoing climate change across their range, although numerous other factors should  
431 also be considered including multiple biogeochemical metrics, colony recruitment and individual  
432 fitness (Paredes et al. 2012; Smith and Reeves 2012; Sydeman et al. 2012). However, our  
433 analysis provides a snapshot of niche characteristics at a singular time frame that may assist with  
434 colony-wide resiliency predictions in combination with future research on changing niche  
435 dynamics at these colonies.

436         When grouped for similarity, niche size generated the following pattern in our study:  
437 Iceland, East Bay Island and Faroe Islands > Christiansø and John's Island > Kongsfjorden,  
438 Alaska and Russia > Tern Island and Grindøya (Figure 1). Using our 3-dimensional view of  
439 niche size, we predict that colonies with wider (i.e., more generalist) 3-dimensional niches such  
440 as those in Iceland and Faroe Islands, or colonies comprised of migrants from multiple locations  
441 such as East Bay will show greater resiliency to shifts in food web dynamics compared to  
442 colonies with a smaller (i.e., more restricted, specialist) niche similar to Tern Island and  
443 Grindøya. Smaller niches are predicted to be a disadvantage in a changing climate as these  
444 alterations may change or eliminate food sources, leaving a colony or species more vulnerable if  
445 they do not have the flexibility to adapt and shift their diet with this changing prey base (Both et  
446 al. 2010; Le Bohec et al. 2013; Ceia and Ramos 2015). However, climate change may present an  
447 opportunity for Arctic colonies with smaller niches to expand their prey sources with advancing  
448 phenology of spring phytoplankton blooms and more open water sources. For those with broader

449 niches at southern latitudes, that niche size may be critical as we see further changes in the  
450 distribution and availability of key prey (Staudinger et al. 2019). Nevertheless, more research  
451 that integrates measures of breeding success and colony demographics is necessary to test these  
452 resiliency hypotheses over long temporal scales to identify seasonal and annual variation in inter-  
453 and intra- colony foraging ecology.

#### 454 ***4.2. Variation in niche size, niche metrics and THg to colony sea-ice cover***

455 Colony niche size was not correlated with sea-ice cover, possibly attributable to several factors.  
456 First, despite the presence of sea ice likely restricting foraging locations, eiders may still be able  
457 to access a diversity of resources, including the potential for prey sources such as ice-associated  
458 amphipods as niche size was similar to southern locations that have more accessible, ice-free  
459 areas (Karnovsky et al. 2008). Second, northern colonies may support a variety of individuals  
460 that utilize both generalist and specialist strategies, thus adding to the flexibility and diversity of  
461 the colony in the face of environmental change (Woo et al. 2008; Ceia and Ramos 2015; Pratte et  
462 al. 2019). Notably, the relative proportion of generalist and specialist individuals in populations  
463 dramatically affects dietary niche size with generalist-based populations having wider niches  
464 (Newsome et al. 2007).

465 We found that eider colonies with greater sea-ice cover had higher  $\delta^{13}\text{C}$  values, which is  
466 not consistent with the expected gradient based on ocean temperature (Sackett et al. 1965;  
467 Goericke and Fry 1994; McMahon et al. 2013). However, this pattern can be most likely  
468 explained by eiders foraging on more resources derived from ice algae with higher ice cover  
469 versus more phytoplankton-derived resources in areas with lower sea-ice presence (Hobson et al.  
470 1995; Tamelander et al. 2006; McMahon et al. 2006). As well, macroalgal carbon has a higher  
471  $\delta^{13}\text{C}$  value than phytoplankton and therefore could be a contributing carbon source to these

472 spatial differences. Nonetheless, we show spatial differences in carbon-source use amongst eider  
473 colonies, where some colonies use more phytoplankton-derived carbon than others. Furthermore,  
474 our results suggest that in general, eider colonies with greater sea-ice cover also had higher  
475 median individual THg and  $\delta^{15}\text{N}$ , suggesting that sea-ice presence results in eiders foraging at  
476 higher trophic levels, thus contributing to higher overall THg exposure. Potential reasons for  
477 higher trophic-level foraging include eiders feeding on ice-associated sources of prey prior to  
478 laying, such as amphipods, due to restricted access to benthic prey with sea ice present  
479 (Karnovsky et al. 2008). Amphipods seasonally forage on ice algae and this would decouple  
480 them from the pelagic food web and result in higher  $\delta^{13}\text{C}$  values (Werner 1997; Brown et al.  
481 2017). Furthermore, waters with sea ice present are supersaturated with dissolved THg, thus  
482 further contributing to the elevation of THg in food webs (DiMento et al. 2019). Individual  
483 variation in foraging behaviour is known to have a role in Hg accumulation (Anderson et al.  
484 2009; Braune et al. 2014; Le Croizier et al. 2019) and in our study, individual variation exists  
485 within colonies as demonstrated by the colony ranges.

#### 486 ***4.3. Role of migration in shaping niche dynamics and THg exposure***

487 We expected migratory populations (see Table 1, Figure 1) to have larger niches due to broader  
488 exposure to a variety of environmental conditions and prey types experienced at overwintering,  
489 migratory stopover, and breeding grounds (Herrera 1978; Gómez et al. 2016). In the present  
490 study we found no pattern with migratory behaviour and niche size. However, two of the largest  
491 niche sizes found at two resident colonies (Iceland and Faroe Islands) may stem from colony-  
492 wide expansion in dietary choice due to increased prey availability. This has been reported in  
493 Iceland where eiders within the colony selected a wide array of both benthic and pelagic prey  
494 (Kristjánsson et al. 2013). Waters around Iceland are a mix of Arctic (East-Greenland Current),

495 as well as Atlantic origins (North Atlantic Current), and this, together with greater lack of sea  
496 ice, seem to provide a diverse range of prey options to pre-breeding eiders (Vincent 2010;  
497 Kristjánsson et al. 2013; Casanova-Masjoan et al. 2020). The East Bay Island colony, consisting  
498 of migrants from Greenland and Newfoundland, had the second largest niche size potentially in  
499 part due to a mixing of individuals from both overwintering sites (Steenweg et al. 2017).  
500 Additionally, individual variation in migration distance and strategy within a colony, although  
501 not included in the present study, may lead to broader colony niche ranges (Mallory et al. 2020).

502 Colonies supporting migratory eiders had higher THg concentrations and foraged at  
503 higher trophic levels compared to colonies supporting residents, suggesting that colonies of  
504 migratory individuals have access to higher trophic-level prey, or rely on these prey to store  
505 resources necessary for migration. Colonies with resident eiders with higher individual  $\delta^{13}\text{C}$   
506 levels partially indicate diets with greater foraging based on ice algae, potentially due to residing  
507 at their Arctic breeding sites year-round while migratory colonies move to more suitable areas  
508 with presumably lower sea ice. Combined with our results on colony latitude, these dynamics  
509 suggest that changes in environmental conditions and variability may have different effects on  
510 migratory and resident seabird colonies dependent on future colony flexibility, thus should be  
511 factored into future analyses especially regarding climate change affects within Arctic  
512 ecosystems.

#### 513 ***4.4. Relationship between trophic position, foraging location and THg concentrations***

514 With increasing industrial activity and contaminant deposition due to long-distance transport in  
515 northern latitudes, as well as the release of stored Hg from melting ice and increased erosion of  
516 terrestrial sources (Sorenson et al. 2016, Cossa et al. 2018), Arctic-inhabiting species are  
517 potentially becoming more at risk for contaminants exposure and a suite of possible negative



518 neurological, physiological and reproductive impacts (Dietz et al. 2013; Scheuhammer et al.  
519 2015). This is especially a potential population stability concern for harvested species, such as  
520 common eider, which are an important, harvested species for many Indigenous communities in  
521 the North (Nakashima and Murray 1988; Priest and Usher 2004). Concentrations of THg for the  
522 eider colonies in this study are comparable to those observed in previous eider research  
523 (Provencher et al. 2016; Albert et al. 2019; Ma et al. 2020; Dietz et al. 2021). The mean  
524 concentrations of THg in the Alaska, Christiansø and East Bay colonies were above 0.95 µg/g  
525 dw, suggesting that three of the 10 colonies studied are therefore considered to be above general  
526 environmental background concentrations (Eagles-Smith et al. 2008; Ackerman et al. 2016).  
527 Only 40% of eiders had higher concentrations of THg (above recognized background  
528 concentrations of 0.95 ug/g dw), but these concentrations assign them a general “low risk” status  
529 regarding concerns for health, physiology, behaviour and reproductive effects (Ackerman et al.  
530 2016; Dietz et al. 2019; 2021). The individual eider with the highest Hg level was from the  
531 Iceland colony (2.55 µg/g dw compared to the colony mean of 0.95 µg/g dw), which features  
532 less sea ice than other regions such as Alaska, which had the highest colony THg average (1.23  
533 µg/g dw).

534         With a rapidly declining sea-ice cover, a rise in phytoplankton production and  
535 consumption by eiders could be related to higher, individual THg concentrations (Stern et al.  
536 2012). Combined with our results in section 4.2 showing higher median THg concentrations at  
537 colonies with greater sea-ice cover, our results demonstrate that within colonies, individuals with  
538 greater phytoplankton-based consumption had higher THg concentrations. The relationship  
539 between individual  $\delta^{13}\text{C}$  and THg, combined with effects of trophic position (determined using  
540  $\delta^{15}\text{N}$ ) on THg may potentially have future effects on seabird health, behaviour and reproduction

541 in those with at-risk Hg exposure. However, it is likely that any possible effects would not be  
542 consistent across the entire range of a species, especially given the regional difference in which  
543 climate change is altering the Arctic (Muir et al. 1999; Mallory and Braune 2012; Swart et al.  
544 2015). Nevertheless, we did detect variation among colonies, suggesting regional differences in  
545 the relationship between  $\delta^{13}\text{C}$ , trophic position and THg; for instance, the Christiansø and  
546 Kongsfjorden colonies showed opposite relationships between THg and  $\delta^{13}\text{C}$  (Figure 3). Thus,  
547 while we conducted a broad-scale study into these relationships, more in-depth analyses of the  
548 environmental factors at each site would allow for site-specific investigation into the  
549 relationships between foraging behaviour and THg uptake. Additionally, further knowledge of  
550 baseline variation (THg,  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$ ) in colony-specific prey at a varying spatio-temporal scale,  
551 parallel with eider sampling, would aid future interpretation of eider niche size and sources of  
552 individual and colony THg. The contribution of terrestrial carbon sources and agricultural runoff  
553 to marine areas around some of these colonies may also contribute to variation in individual  $\delta^{13}\text{C}$   
554 and  $\delta^{15}\text{N}$  values and affect the rate of THg accumulation (Dunton et al. 2006; Laursen et al.  
555 2018; Renedo et al. 2020). Overall, the relationship between environmental conditions and THg  
556 concentrations presents a complex system and paired with the rapid changes in ecosystem  
557 dynamics currently being observed (i.e., sea ice abundance), underscores the necessity of future,  
558 and consistent annual monitoring, especially in key ecosystem indicators like seabirds.

## 559 **5. Conclusion**

560 We examined inter-colony, 3-dimensional niche size, isotopic and THg ranges, and the  
561 relationships between  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and THg within individuals. Our results suggest that common  
562 eider colonies across the Arctic and subarctic have a wide degree of diet variation, potentially  
563 influenced by environmental changes including spatio-temporal differences in primary

564 productivity. We found that consideration of colony-level variation in life histories (migratory vs  
565 resident) was important for assessing the level of risk to which a colony may be exposed.  
566 Further, inter-annual multidimensional niche analyses would provide greater insight into the  
567 temporal variation in niche size that exists at both an inter- and intra-colony scale. Taken  
568 together, exploring multidimensional niche metrics is an increasingly valuable tool to provide  
569 insight into how diet breadth differs across a species' range, especially when combined with  
570 temporal and spatial variation in environmental conditions and key components to variation in  
571 life history such as migration.

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1126

1127 **Tables and Figures**

1128 **Table 1.** Locations of common eider colonies included in this study, sample size (number of  
 1129 individual birds from each colony included in the study), month samples were obtained,  
 1130 coordinates (latitude and longitude), whether a colony is known to be predominately migratory  
 1131 or resident, and the proportion of sea ice cover in a 100km area around the colony during the  
 1132 appropriate timeframe reflecting isotope data.

<b>Location</b>	<b>n</b>	<b>Sampling month</b>	<b>Latitude</b>	<b>Longitude</b>	<b>Migratory behaviour</b>	<b>Sea ice cover</b>
Kaktovik, Alaska	33	July	70.340	-147.776	Migratory	43.45
Breiðafjörður, Iceland	23	June	65.078	-22.736	Resident	3.10
Christiansø, Denmark	25	May	55.330	15.188	Migratory	0
Grindøya, Norway	17	June	69.633	18.844	Resident	0
John's Island, Canada	19	July	43.645	-66.041	Migratory	0
Kirkjubøhólmur, Faroe Islands	16	July	61.950	-6.799	Resident	0
Kongsfjorden, Norway	16	June	78.918	11.910	Migratory	0
East Bay Island, Canada	43	June	64.023	-81.790	Migratory	34.34
Onega Bay, Russia	24	June	65.048	35.774	Resident	0
Tern Island, Canada	24	June	69.547	-80.812	Migratory	36.47

1133

1134 Table 2. Isotopic signatures ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  in ‰) of typical common eider bivalve prey as  
 1135 determined by the most spatio-temporally appropriate literature values available at the time of  
 1136 analysis. Prey stable isotope data was used to correct common eider isotope data to allow for  
 1137 inter-colony comparison.

Location	Prey Species	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	Reference
Beaufort Sea, Alaska	<i>Cyrtodaria kurriana</i>	-25.20	7.90	Dunton et al. 2012
Breiðafjörður, Iceland	<i>Mytilus edulis</i>	-19.60	7.40	Sarà et al. 2007
Christiansø, Denmark	<i>Limecola balthica</i>	-20.40	7.20	Ek et al. 2018
Grindøya, Norway	<i>Hiatella arctica</i>	-19.32	7.26	Fredriksen 2003
John's Island, Canada	<i>Mytilus edulis</i>	-19.99	7.17	English et al. 2015
Kirkjubøhólmur, Faroe Islands	<i>Mytilus edulis</i>	-19.20	8.41	Bustamante, unpub.
Kongsfjorden, Norway	<i>Hiatella arctica</i>	-20.30	6.90	Vieweg et al. 2012
East Bay Island, Canada	<i>Hiatella arctica</i>	-18.22	8.64	Sénéchal et al. 2011
Onega Bay, Russia	<i>Styela rustica</i>	-21.60	6.49	Yakovis et al. 2012
Tern Island, Canada	<i>Hiatella arctica</i>	-18.22	8.64	Sénéchal et al. 2011

1138

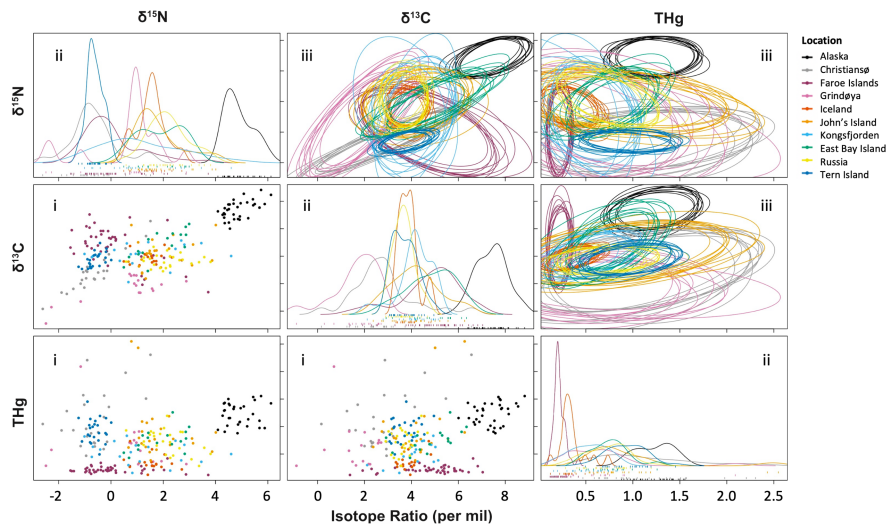
1139 **Table 3.** Results of three sets of statistical analyses: a) seven 2-tailed t-tests relating migratory  
 1140 status to colony niche size, isotope and THg ranges, as well as individual colony-corrected  
 1141 isotope and THg values; b) seven GLM results relating colony sea ice cover to colony niche size,  
 1142 isotope and THg ranges as well as median colony isotope and THg values; c) GLMM results  
 1143 relating common eider trophic position, calculated using baseline and individual  $\delta^{15}\text{N}$  and  
 1144 colony-corrected  $\delta^{13}\text{C}$  to individual THg values. All log-transformed values were determined  
 1145 using the natural log and used to meet model assumptions.

Variable	Estimate ( $\beta$ )	SE	df	t	p
<b>a) 2-tailed t-test – Migratory Status</b>					
log(Niche size)			4	-0.609	0.573
log( $\delta^{13}\text{C}$ Range)			8	-0.339	0.743
$\delta^{15}\text{N}$ Range			7	0.996	0.353
log(THg Range)			5	-0.600	0.576
<b>Individual <math>\delta^{13}\text{C}</math></b>			238	2.218	<b>0.028</b>
<b>Individual <math>\delta^{15}\text{N}</math></b>			220	-6.858	<b>&lt;0.001</b>
<b>log(Individual THg)</b>			124	-6.329	<b>&lt;0.001</b>
<b>b) GLM – Sea Ice Cover</b>					
log(Niche size)	-0.0125	0.019	8	-0.639	0.541
log( $\delta^{13}\text{C}$ Range)	-0.013	0.008	8	-1.635	0.141
$\delta^{15}\text{N}$ Range	-0.002	0.014	8	-0.106	0.919
log(THg Range)	-0.004	0.009	8	-0.459	0.658
<b>log(Median <math>\delta^{13}\text{C}</math>)</b>	0.028	0.010	8	2.936	<b>0.032</b>
<b>Median <math>\delta^{15}\text{N}</math></b>	0.052	0.022	8	2.332	<b>0.048</b>
<b>log(Median THg)</b>	0.014	0.006	8	2.525	<b>0.036</b>
<b>c) GLMM – Individual log(THg)</b>					
Intercept	-1.923	0.304	142.233	-6.330	<0.0001
<b>Trophic position</b>	0.563	0.096	234.614	5.862	<b>&lt;0.001</b>
<b><math>\delta^{13}\text{C}</math></b>	-0.063	0.022	232.943	-2.813	<b>0.005</b>



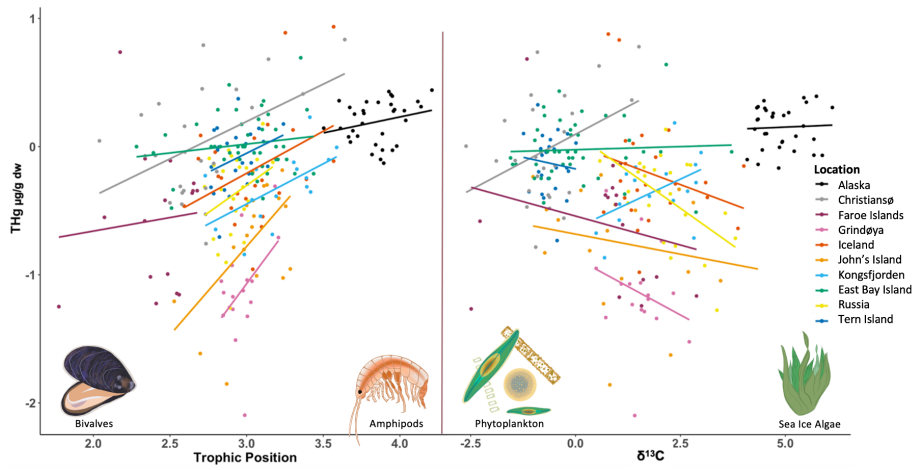
1146  
 1147 **Figure 1.** Map of the circumpolar-Arctic, and locations of the 10 common eider colonies used in  
 1148 this study (stars) designated by whether a colony is primarily resident (circles) or migratory  
 1149 (squares). Shape colour represents four groupings of similar median 3-dimensional niche size  
 1150 (95% Bayesian credible intervals). By ascending niche size, colours represent: 1 (smallest; red),  
 1151 2 (white), 3 (grey), and 4 (largest; black). Dashed line indicates the Arctic Circle, and the solid  
 1152 line indicates the Arctic boundary according to the Arctic Monitoring and Assessment  
 1153 Programme (AMAP; map provided by [globalcitymap.com](http://globalcitymap.com)).





1154

1155 **Figure 2.** 2-dimensional projections of ten 3-dimensional niche regions produced using the R  
 1156 package nicheROVER v1.0 (Swanson et al. 2015). Corrected stable isotope ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  in  
 1157 ‰) and THg data (in  $\mu\text{g/g dw}$ ) were used from individuals at 10 pan-Arctic or subarctic common  
 1158 eider colonies. Sections show, i) The raw stable isotope and THg data in pairs, ii) density  
 1159 estimates of  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$  and THg individually, and iii) pairings of  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$  and THg showing 2-  
 1160 dimensional projections of 95% probabilistic niche regions based on 3-dimensional data.



1161

1162 **Figure 3.** Relationship between THg (natural log-transformed) with trophic position (calculated  
 1163 based on  $\delta^{15}\text{N}$ ; see Methods) and colony-corrected  $\delta^{13}\text{C}$  (in ‰) for individuals at 10 pan-Arctic  
 1164 or subarctic common eider colonies, identified by colour.

1165

1166 **Supplemental Materials**

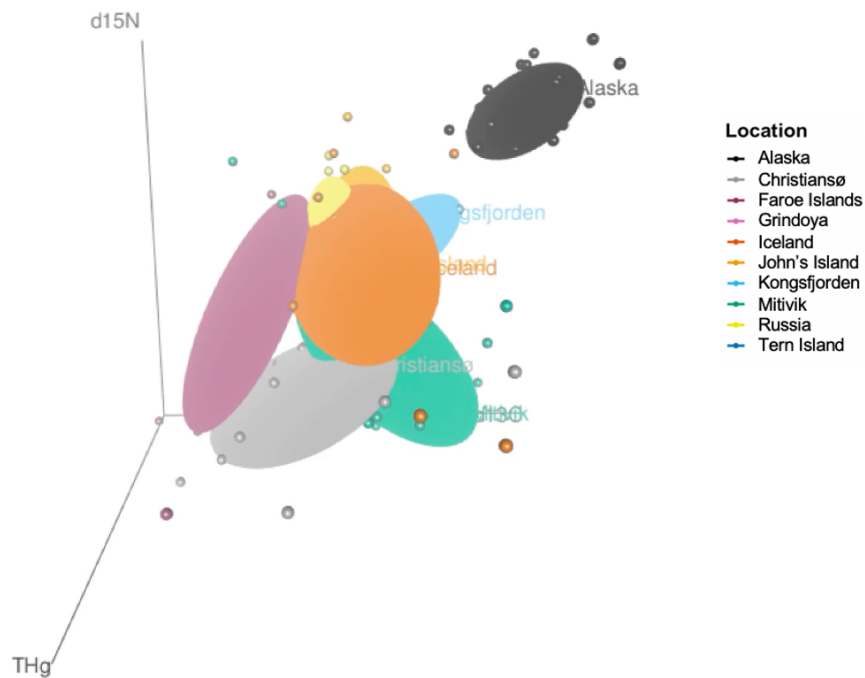
1167 Sample sizes (n), means  $\pm$  SD, Min-Max (in %) for  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and total Hg (THg in  $\mu\text{g/g dw}$ )  
 1168 (values in brackets corrected for colony baseline ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ) and standardized for units ( $\delta^{13}\text{C}$ ,  
 1169  $\delta^{15}\text{N}$  and THg)), medians and range of 3-dimensional niche size (95% Bayesian credible  
 1170 intervals), and  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and THg ranges (maximum-minimum values using corrected and  
 1171 standardized values) of 10 pan-Arctic and subarctic common eider colonies.

Location	n	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	THg	Niche size	$\delta^{13}\text{C}$ range	$\delta^{15}\text{N}$ range	THg range
Alaska	33	-20.1 $\pm$ 0.5 (1.8)	15.3 $\pm$ 0.7 (1.8)	1.2 $\pm$ 0.2 (0.9)	3.3 (2.3, 5.2)	0.866	1.461	1.689
Christiansø	25	-21.2 $\pm$ 0.9 (-1.0)	10.0 $\pm$ 1.3 (-0.9)	1.1 $\pm$ 0.5 (0.6)	9.7 (6.6, 16.7)	1.379	2.923	4.590
Faroe Islands	16	-18.5 $\pm$ 1.4 (-0.3)	10.1 $\pm$ 1.0 (-1.5)	0.7 $\pm$ 0.4 (-0.6)	18.8 (11.5, 36.8)	2.059	2.106	4.508
Grindøya	17	-17.8 $\pm$ 0.6 (0.1)	11.1 $\pm$ 0.4 (-0.3)	0.4 $\pm$ 0.1 (-1.4)	1.4 (0.8, 2.6)	0.834	0.907	1.528
Iceland	23	-17.8 $\pm$ 0.9 (0.3)	11.6 $\pm$ 1.0 (-0.1)	0.9 $\pm$ 0.5 (0.1)	21.7 (14.2, 37.7)	1.407	2.257	5.410
John's Island	19	-16.9 $\pm$ 1.5 (-0.1)	12.0 $\pm$ 0.8 (-0.1)	0.5 $\pm$ 0.2 (-0.9)	9.1 (5.7, 16.5)	2.250	1.633	1.688
Kongsfjorden	16	-18.4 $\pm$ 0.8 (0.3)	11.8 $\pm$ 1.0 (0.3)	0.8 $\pm$ 0.2 (-0.3)	4.6 (2.8, 9.1)	1.217	2.128	2.068
East Bay Island	43	-18.2 $\pm$ 1.1 (-0.6)	13.5 $\pm$ 1.3 (0.3)	1.0 $\pm$ 0.3 (0.4)	18.5 (13.6, 27.9)	1.904	2.897	3.571
Russia	24	-19.4 $\pm$ 0.8 (0.4)	10.2 $\pm$ 0.4 (-0.4)	0.7 $\pm$ 0.2 (-0.4)	3.3 (2.2, 5.8)	1.175	0.962	2.278
Tern Island	24	-18.8 $\pm$ 0.3 (-1.0)	12.4 $\pm$ 0.5 (-0.4)	0.9 $\pm$ 0.2 (0.1)	1.4 (0.9, 2.4)	0.475	1.141	2.398

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1173

1174 3-dimensional representation of ten 3-dimensional niche regions produced using the R package  
1175 rgl v.0.100.54 (Adler and Murdoch 2017). Corrected stable isotope values ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  in ‰)  
1176 and THg concentrations (in  $\mu\text{g}/\text{g}$  dw) were used from individuals at ten pan-Arctic or subarctic  
1177 common eider colonies to obtain 3-dimensional niche regions using the R package nicheROVER  
1178 v1.0 (Swanson et al. 2015).



1179  
1180 (Still image of a video showing the 3-dimensional plot in rotating view).