



HAL
open science

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

Reyd Smith, David Yurkowski, Kyle J.L. Parkinson, Jérôme Fort, Holly Hennin, H. Grant Gilchrist, Keith Hobson, Mark Mallory, Jóhannis Danielsen, Svend Garbus, et al.

► To cite this version:

Reyd Smith, David Yurkowski, Kyle J.L. Parkinson, Jérôme Fort, Holly Hennin, et al.. Environmental and life-history factors influence inter-colony multidimensional niche metrics of a breeding Arctic marine bird. *Science of the Total Environment*, 2021, 796, pp.148935. 10.1016/j.scitotenv.2021.148935 . hal-03346864

HAL Id: hal-03346864

<https://hal.science/hal-03346864v1>

Submitted on 25 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

3 Reyd A. Smith^{1*}, David J. Yurkowski², Kyle J.L. Parkinson¹, Jérôme Fort³, Holly L. Hennin⁴, H.
4 Grant Gilchrist⁴, Keith A. Hobson⁵, Mark L. Mallory⁶, Jóhannis Danielsen⁷, Svend E. Garbus⁸,
5 Sveinn A. Hanssen⁹, Jón Einar Jónsson¹⁰, Christopher J. Latty¹¹, Ellen Magnúsdóttir¹⁰, Børge
6 Moe⁹, Glen J. Parsons¹², Christian Sonne⁸, Grigori Tertitski¹³, and Oliver P. Love¹

7
8 ¹ University of Windsor, Windsor, Ontario, Canada, N9B 3P4

9 ² Fisheries and Oceans Canada, Winnipeg, Manitoba, Canada, R3T 2N6

10 ³ French National Centre for Scientific Research, Paris, France, 75016

11 ⁴ Environment and Climate Change Canada, Ottawa, Ontario, Canada, K0A 1H0.

12 ⁵ Western University, London, Ontario, Canada, N6A 3K7

13 ⁶ Acadia University, Wolfville, Nova Scotia, Canada, B4P 2R6

14 ⁷ Faroe Marine Research Institute, Tórshavn, Faroe Islands, FO-110

15 ⁸ Aarhus University, Roskilde, Denmark, DK-4000

16 ⁹ Norwegian Institute for Nature Research, Tromsø, Norway, N-9296

17 ¹⁰ University of Iceland's Research Centre at Snæfellsnes, Hafnargata 3, 340, Stykkishólmur,
18 Iceland

19 ¹¹ Arctic National Wildlife Refuge, U.S. Fish and Wildlife Service, Fairbanks, Alaska, United
20 States, 99701

21 ¹² Nova Scotia Department of Lands and Forestry, Kentville, Nova Scotia, Canada, B4N 4E5

22 ¹³ Institute of Geography of the Russian Academy of Sciences, Moscow, Russia, 119017

23

24 *Corresponding Author

25

26

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}C -depleted
91 phytoplankton-derived carbon and ^{13}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}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 μL 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 N₂ and CO₂ 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 ± 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 N₂ and CO₂ 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 (δ) 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 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}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 (TP_{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 ± 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.

572 **Acknowledgments**

573 We thank the field crews and regional volunteers at all locations who assisted in sample
574 collection and logistics. As well, thank you to the lab technicians at Research and Productivity
575 Council (RPC) in New Brunswick, Canada and Littoral Environment et Sociétés (LIENSs, La
576 Rochelle) for sample analysis. We are also grateful to the plateformes 'Analyses Élémentaires'
577 and 'Spectrométrie Isotopique' (La Rochelle University - LIENSs) for their assistance with
578 laboratory work. We also thank Environment and Climate Change Canada (ECCC), the Natural
579 Sciences and Engineering Research Council of Canada, Canada Research Chairs Program, the
580 Nunavut Wildlife Management Board, Northern Scientific Training Program, Polar Continental
581 Shelf Project, Polar Knowledge Canada, Baffinland Iron Mine, the Canadian Network of Centres
582 of Excellence (ArcticNet), Mitacs Globalink Research, The Danish Environmental Protection
583 Agency, Danish Hunters' Association, Hunters' Nature Fund, the Government of Ontario and the
584 University of Windsor for logistical support, research and/or personal funding. This study is also
585 a contribution to the ARCTOX initiative (arctox.cnrs.fr) and the ARCTIC-STRESSORS project
586 (ANR-20-CE34-0006-01). Animal care approval for this project was granted through the

587 University of Windsor Committee for Animal Care (AUPP #11-06; Reproductive Strategies of
588 Arctic-Breeding Common Eiders), and ECCC Animal Care (EC-PN-15-026).
589

590 **Literature Cited**

- 591 Ackerman, J.T., Eagles-Smith, C.A., Herzog, M.P., Hartman, C.A., Peterson, S.H., Evers, D.C.,
592 Jackson, A.K., Elliott, J.E., Vander Pol, S.S. and Bryan, C.E. 2016. Avian mercury
593 exposure and toxicological risk across western North America: a synthesis. *Science of the*
594 *Total Environment*, 568: 749-769.
- 595 Adler, D. and Murdoch, D. 2017. 3D Visualization Using OpenGL. Web page: [[https://cran.r-](https://cran.r-project.org/web/packages/rgl/rgl.pdf)
596 [project.org/web/packages/rgl/rgl.pdf](https://cran.r-project.org/web/packages/rgl/rgl.pdf)].
- 597 Akearok, J.A., Hebert, C.E., Braune, B.M. and Mallory, M.L. 2010. Inter-and intraclutch
598 variation in egg mercury levels in marine bird species from the Canadian Arctic. *Science*
599 *of the Total Environment*, 408(4): 836-840.
- 600 Albert, C., Renedo, M., Bustamante, P. and Fort, J. 2019. Using blood and feathers to investigate
601 large-scale Hg contamination in Arctic seabirds: a review. *Environmental Research*, 177:
602 108588.
- 603 Albert, C., Helgason, H.H., Brault-Favrou, M., Robertson, G.J., Descamps, S., Amélineau, F.,
604 Danielsen, J., Dietz, R., Elliott, K., Erikstad, K.E. and Eulaers, I., Ezhov, A.,
605 Fitzsimmons, M.G., Gavriilo, M., Golubova, E., Grémillet, D., Hatch, H., Huffeldt, N.P.,
606 Jakubas, D., Kitaysky, A., Kolbeinsson, Y., Krasnov, Y., Lorentsen, S.A., Lorentzen, E.,
607 Mallory, M.L., Merkel, B., Merkel, F.R., Montevecchi, W., Mosbech, A., Olsen, B.,
608 Orben, R.A., Patterson, A., Provencher, J., Plumejeaud, C., Pratte, I., Reiertsen, T.K.,
609 Renner, H., Rojek, N., Romano, M., Strøm, H., Systad, G.H., Takahashi, A., Thiebot,
610 J.B., Thórarinnsson, T.L., Will, A.P., Wojczulanis-Jakubas, K., Bustamante, P. and Fort, J.
611 2021. Seasonal variation of mercury contamination in Arctic seabirds: a pan-arctic
612 assessment. *Science of the Total Environment*, 750: 142201.

613 Anderson, O.R.J., Phillips, R.A., McDonald, R.A., Shore, R.F., McGill, R.A.R. and Bearhop, S.
614 2009. Influence of trophic position and foraging range on mercury levels within a seabird
615 community. *Marine Ecology Progress Series*, 375: 277-288.

616 Araújo, M.S., Bolnick, D.I. and Layman, C.A. 2011. The ecological causes of individual
617 specialisation. *Ecology Letters*, 14(9): 948-958.

618 Atwell, L., Hobson, K.A. and Welch, H.E. 1998. Biomagnification and bioaccumulation of
619 mercury in an arctic marine food web: insights from stable nitrogen isotope analysis.
620 *Canadian Journal of Fisheries and Aquatic Sciences*, 55(5): 1114-1121.

621 Barber, D.G., Hop, H., Mundy, C.J., Else, B., Dmitrenko, I.A., Tremblay, J.E., Ehn, J.K., Assmy,
622 P., Daase, M., Candlish, L.M. and Rysgaard, S. 2015. Selected physical, biological and
623 biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. *Progress in*
624 *Oceanography*, 139: 122-150.

625 Barquete, V., Strauss, V. and Ryan, P.G. 2013. Stable isotope turnover in blood and claws: a
626 case study in captive African penguins. *Journal of Experimental Marine Biology and*
627 *Ecology*, 448: 121-127.

628 Bearhop, S., Phillips, R.A., Thompson, D.R., Waldron, S. and Furness, R.W. 2000. Variability in
629 mercury concentrations of great skuas *Catharacta skua*: the influence of colony, diet and
630 trophic status inferred from stable isotope signatures. *Marine Ecology Progress Series*,
631 195: 261-268.

632 Bearhop, S., Waldron, S., Votier, S.C. and Furness, R.W. 2002. Factors that influence
633 assimilation rates and fractionation of nitrogen and carbon stable isotopes in avian blood
634 and feathers. *Physiological and Biochemical Zoology*, 75(5): 451-458.

635 Bearhop, S., Phillips, R.A., McGill, R., Cherel, Y., Dawson, D.A. and Croxall, J.P. 2006. Stable
636 isotopes indicate sex-specific and long-term individual foraging specialisation in diving
637 seabirds. *Marine Ecology Progress Series*, 311: 157-164.

638 Bolnick, D.I., Svanbäck, R., Fordyce, J.A., Yang, L.H., Davis, J.M., Hulseley, C.D. and Forister,
639 M.L. 2003. The ecology of individuals: incidence and implications of individual
640 specialization. *The American Naturalist*, 161(1): 1-28.

641 Bond, A.L. and Diamond, A.W. 2011. Recent Bayesian stable-isotope mixing models are highly
642 sensitive to variation in discrimination factors. *Ecological Applications*, 21(4): 1017-
643 1023.

644 Bønløkke, J., Madsen, J.J., Thorup, K., Pedersen, K.T., Bjerrum, M. and Rahbek, C. 2006.
645 Dansk Trækfugleatlas: the Danish bird migration atlas. Rhodos.

646 Both, C., Van Turnhout, C.A., Bijlsma, R.G., Siepel, H., Van Strien, A.J. and Foppen, R.P. 2010.
647 Avian population consequences of climate change are most severe for long-distance
648 migrants in seasonal habitats. *Proceedings of the Royal Society B: Biological Sciences*,
649 277(1685): 1259-1266.

650 Bottitta, G.E., Nol, E. and Gilchrist, H.G. 2003. Effects of experimental manipulation of
651 incubation length on behavior and body mass of common eiders in the Canadian Arctic.
652 *Waterbirds*, 26(1): 100-107.

653 Bowen, G.J. 2010. Isoscapes: spatial pattern in isotopic biogeochemistry. *Annual Review of*
654 *Earth and Planetary Sciences*, 38: 161-187.

655 Braune, B.M., Outridge, P.M., Fisk, A.T., Muir, D.C.G., Helm, P.A., Hobbs, K., Hoekstra, P.F.,
656 Kuzyk, Z.A., Kwan, M., Letcher, R.J. and Lockhart, W.L. 2005. Persistent organic

657 pollutants and mercury in marine biota of the Canadian Arctic: an overview of spatial and
658 temporal trends. *Science of the Total Environment*, 351: 4-56.

659 Braune, B.M., Scheuhammer, A.M., Crump, D., Jones, S., Porter, E. and Bond, D. 2012.
660 Toxicity of methylmercury injected into eggs of thick-billed murre and arctic terns.
661 *Ecotoxicology*, 21(8): 2143-2152.

662 Braune, B.M., Gaston, A.J., Hobson, K.A., Gilchrist, H.G. and Mallory, M.L. 2014. Changes in
663 food web structure alter trends of mercury uptake at two seabird colonies in the Canadian
664 Arctic. *Environmental Science and Technology*, 48(22): 13246-13252.

665 Brown, T.A., Assmy, P., Hop, H., Wold, A. and Belt, S.T. 2017. Transfer of ice algae carbon to
666 ice-associated amphipods in the high-Arctic pack ice environment. *Journal of Plankton
667 Research*, 39(4): 664-674.

668 Cardona-Marek, T., Knott, K.K., Meyer, B.E. and O'Hara, T.M. 2009. Mercury concentrations in
669 southern Beaufort Sea polar bears: variation based on stable isotopes of carbon and
670 nitrogen. *Environmental Toxicology and Chemistry: An International Journal*, 28(7):
671 1416-1424.

672 Carleton, S.A. and Del Rio, C.M. 2005. The effect of cold-induced increased metabolic rate on
673 the rate of ¹³C and ¹⁵N incorporation in house sparrows (*Passer domesticus*).
674 *Oecologia*, 144(2): 226-232.

675 Casanova-Masjoan, M., Pérez-Hernández, M.D., Pickart, R.S., Valdimarsson, H., Ólafsdóttir,
676 S.R., Macrander, A., Grisolia-Santos, D., Torres, D.J., Jónsson, S., Våge, K. and Lin, P.
677 2020. Along-stream, seasonal, and interannual variability of the north Icelandic Irminger
678 Current and East Icelandic Current around Iceland. *Journal of Geophysical Research:
679 Oceans*, 125(9): e2020JC016283.

680 Ceia, F.R. and Ramos, J.A. 2015. Individual specialization in the foraging and feeding strategies
681 of seabirds: a review. *Marine Biology*, 162(10): 1923-1938.

682 Chen, D. and Hale, R.C. 2010. A global review of polybrominated diphenyl ether flame retardant
683 contamination in birds. *Environment International*, 36(7): 800-811.

684 Cherel, Y., Hobson, K.A., Bailleul, F. and Groscolas, R. 2005. Nutrition, physiology, and stable
685 isotopes: new information from fasting and molting penguins. *Ecology*, 86(11): 2881-
686 2888.

687 Cherel, Y. and Hobson, K.A. 2007. Geographical variation in carbon stable isotope signatures of
688 marine predators: a tool to investigate their foraging areas in the Southern Ocean. *Marine
689 Ecology Progress Series*, 329: 281-287.

690 Cossa, D.; Heimbürger, L. E.; Sonke, J. E.; Planquette, H.; Lherminier, P.; García-Ibáñez, M. I.;
691 Pérez, F. F.; Sarthou, G. 2018. Sources, cycling and transfer of mercury in the Labrador
692 Sea (Geotraces-Geovide cruise). *Marine Chemistry* 198:64–69.

693 Cusset, F., Fort, J., Mallory, M., Braune, B., Massicotte, P. and Massé, G. 2019. Arctic seabirds
694 and shrinking sea ice: egg analyses reveal the importance of ice-derived
695 resources. *Scientific Reports*, 9(1): 1-15.

696 de la Vega, C., Jeffreys, R.M., Tuerena, R., Ganeshram, R. and Mahaffey, C. 2019. Temporal
697 and spatial trends in marine carbon isotopes in the Arctic Ocean and implications for food
698 web studies. *Global Change Biology*, 25(12): 4116-4130.

699 Dietz, R., Outridge, P.M. and Hobson, K.A. 2009. Anthropogenic contributions to mercury
700 levels in present-day Arctic animals—a review. *Science of the Total Environment*,
701 407(24): 6120-6131.

a mis en forme : Français

702 Dietz, R., Sonne, C., Basu, N., Braune, B., O'Hara, T., Letcher, R.J., Scheuhammer, T.,
703 Andersen, M., Andreassen, C., Andriashek, D. and Asmund, G. 2013. What are the
704 toxicological effects of mercury in Arctic biota? *Science of the Total Environment*, 443:
705 775-790.

706 Dietz, R., Letcher, R.J., Desforages, J.P., Eulaers, I., Sonne, C., Wilson, S., Andersen-Ranberg,
707 E., Basu, N., Barst, B.D., Bustnes, J.O. and Bytingsvik, J. 2019. Current state of
708 knowledge on biological effects from contaminants on Arctic wildlife and fish. *Science*
709 *of the Total Environment*, 696: 133792.

710 Dietz, R., Fort, J., Sonne, C., Albert, C., Bustnes, J.O., Christensen, T.K., Ciesielski, T.M.,
711 Danielsen, J., Dastnai, S., Eens, M. and Erikstad, K.E. 2021. A risk assessment of the
712 effects of mercury on Baltic Sea, Greater North Sea and North Atlantic wildlife, fish and
713 bivalves. *Environment International*, 146: 106178.

714 DiMento, B.P., Mason, R.P., Brooks, S. and Moore, C. 2019. The impact of sea ice on the air-sea
715 exchange of mercury in the Arctic Ocean. *Deep Sea Research Part I: Oceanographic*
716 *Research Papers*, 144: 28-38.

717 Dunton, K.H., Weingartner, T. and Carmack, E.C. 2006. The nearshore western Beaufort Sea
718 ecosystem: circulation and importance of terrestrial carbon in arctic coastal food
719 webs. *Progress in Oceanography*, 71(2-4): 362-378.

720 Dunton, K.H., Schonberg, S.V. and Cooper, L.W. 2012. Food web structure of the Alaskan
721 nearshore shelf and estuarine lagoons of the Beaufort Sea. *Estuaries and Coasts*, 35(2):
722 416-435.

723 Eagles-Smith, C.A., Ackerman, J.T., Adelsbach, T.L., Takekawa, J.Y., Miles, A.K. and Keister,
724 R.A. 2008. Mercury correlations among six tissues for four waterbird species breeding in

725 San Francisco Bay, California, USA. *Environmental Toxicology and Chemistry: An*
726 *International Journal*, 27(10): 2136-2153.

727 Ek, C., Holmstrand, H., Mustajärvi, L., Garbaras, A., Barisevičiūtė, R., Šapolaitė, J., Sobek, A.,
728 Gorokhova, E. and Karlson, A.M. 2018. Using compound-specific and bulk stable
729 isotope analysis for trophic positioning of bivalves in contaminated Baltic Sea sediments.
730 *Environmental Science & Technology*, 52(8): 4861-4868.

731 English, M.D., Robertson, G.J. and Mallory, M.L. 2015. Trace element and stable isotope
732 analysis of fourteen species of marine invertebrates from the Bay of Fundy,
733 Canada. *Marine Pollution Bulletin*, 101(1): 466-472.

734 Evers, D. 2018. The effects of methylmercury on wildlife: a comprehensive review and approach
735 for interpretation. *The Encyclopedia of the Anthropocene*, 5: 181-194.

736 Federer, R.N., Hollmen, T.E., Esler, D., Wooller, M.J. and Wang, S.W. 2010. Stable carbon and
737 nitrogen isotope discrimination factors from diet to blood plasma, cellular blood, feathers,
738 and adipose tissue fatty acids in Spectacled Eiders (*Somateria fischeri*). *Canadian Journal*
739 *of Zoology*, 88(9): 866-874.

740 Fort, J., Robertson, G.J., Grémillet, D., Traisnel, G. and Bustamante, P. 2014. Spatial
741 ecotoxicology: migratory Arctic seabirds are exposed to mercury contamination while
742 overwintering in the northwest Atlantic. *Environmental Science and Technology*, 48(19):
743 11560-11567.

744 Fort, J., Grémillet, D., Traisnel, G., Amélineau, F. and Bustamante, P. 2016. Does temporal
745 variation of mercury levels in Arctic seabirds reflect changes in global environmental
746 contamination, or a modification of Arctic marine food web functioning? *Environmental*
747 *Pollution*, 211: 382-388.

748 France, R.L. 1995. Differentiation between littoral and pelagic food webs in lakes using stable
749 carbon isotopes. *Limnology and Oceanography*, 40(7): 1310-1313.

750 Fredriksen, S. 2003. Food web studies in a Norwegian kelp forest based on stable isotope ($\delta^{13}\text{C}$
751 and $\delta^{15}\text{N}$) analysis. *Marine Ecology Progress Series*, 260: 71-81.

752 Frederiksen, M., Edwards, M., Richardson, A.J., Halliday, N.C. and Wanless, S. 2006. From
753 plankton to top predators: bottom-up control of a marine food web across four trophic
754 levels. *Journal of Animal Ecology*, 75(6): 1259-1268.

755 Foster, K.L., Braune, B.M., Gaston, A.J. and Mallory, M.L. 2019. Climate influence on mercury
756 in Arctic seabirds. *Science of The Total Environment*, 693: 133569.

757 Fox, J. and Weisberg, S. 2019. *An R companion to applied regression (Third)*. Thousand Oaks
758 CA: Sage.

759 Goericke, R. and Fry, B. 1994. Variations of marine plankton $\delta^{13}\text{C}$ with latitude, temperature,
760 and dissolved CO_2 in the world ocean. *Global Biogeochemical Cycles*, 8(1): 85-90.

761 Gómez, C., Tenorio, E.A., Montoya, P. and Cadena, C.D. 2016. Niche-tracking migrants and
762 niche-switching residents: evolution of climatic niches in New World warblers
763 (Parulidae). *Proceedings of the Royal Society B: Biological Sciences*, 283(1824):
764 20152458.

765 Goudie, R.I., Robertson, G.J. and Reed, A. 2020. Common eider (*Somateria mollissima*), version
766 1.0. *Birds of the World*. Cornell Lab of Ornithology, Ithaca, NY.

767 Goutte, A., Barbraud, C., Meillère, A., Carravieri, A., Bustamante, P., Labadie, P., Budzinski,
768 H., Delord, K., Cherel, Y., Weimerskirch, H. and Chastel, O. 2014. Demographic
769 consequences of heavy metals and persistent organic pollutants in a vulnerable long-lived

770 bird, the wandering albatross. *Proceedings of the Royal Society B: Biological Sciences*,
771 281(1787): 20133313.

772 Guzzo, M.M., Blanchfield, P.J., Chapelsky, A.J. and Cott, P.A. 2016. Resource partitioning
773 among top-level piscivores in a sub-Arctic lake during thermal stratification. *Journal of*
774 *Great Lakes Research*, 42(2): 276-285.

775 Hartman, C.A., Ackerman, J.T. and Herzog, M.P. 2019. Mercury exposure and altered parental
776 nesting behavior in a wild songbird. *Environmental Science & Technology*, 53(9): 5396-
777 5405.

778 Hanssen, S., Engebretsen, H. and Erikstad, K. 2002. Incubation start and egg size in relation to
779 body reserves in the common eider. *Behavioral Ecology and Sociobiology*, 52(4): 282-
780 288.

781 Hanssen, S.A., Gabrielsen, G.W., Bustnes, J.O., Bråthen, V.S., Skottene, E., Fenstad, A.A.,
782 Strøm, H., Bakken, V., Phillips, R.A. and Moe, B. 2016. Migration strategies of common
783 eiders from Svalbard: implications for bilateral conservation management. *Polar Biology*,
784 39(11): 2179-2188.

785 Harris, D., Porter, L.K. and Paul, E.A. 1997. Continuous flow isotope ratio mass spectrometry of
786 carbon dioxide trapped as strontium carbonate. *Communications in Soil Science and*
787 *Plant Analysis*, 28(9-10): 747-757.

788 Hennin, H.L., Legagneux, P., Bêty, J., Williams, T.D., Gilchrist, H.G., Baker, T.M. and Love,
789 O.P. 2015. Pre-breeding energetic management in a mixed-strategy breeder. *Oecologia*,
790 177(1): 235-243.

791 Herrera, C.M. 1978. Ecological correlates of residence and non-residence in a Mediterranean
792 passerine bird community. *Journal of Animal Ecology*. 47: 871-890.

793 Hoegh-Guldberg, O. and Bruno, J.F. 2010. The impact of climate change on the world's marine
794 ecosystems. *Science*, 328(5985): 1523-1528.

795 Hobson, K.A., Alisauskas, R.T. and Clark, R.G. 1993. Stable-nitrogen isotope enrichment in
796 avian tissues due to fasting and nutritional stress: implications for isotopic analyses of
797 diet. *The Condor*, 95(2): 388-394.

798 Hobson, K.A., Fisk, A., Karnovsky, N., Holst, M., Gagnon, J.M. and Fortier, M. 2002. A stable
799 isotope ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) model for the North Water food web: implications for evaluating
800 trophodynamics and the flow of energy and contaminants. *Deep Sea Research Part II:
801 Topical Studies in Oceanography*, 49(22-23): 5131-5150.

802 Hobson K.A. 2006. Using stable isotopes to quantitatively track endogenous and exogenous
803 nutrient allocations to eggs of birds that travel to breed. *Ardea*, 94(3): 359–369.

804 Hobson, K.A. and Clark, R.G. 1992. Assessing avian diets using stable isotopes I: turnover of
805 ^{13}C in tissues. *The Condor*, 94(1): 181-188.

806 Hobson, K.A. and Welch, H.E. 1992. Determination of trophic relationships within a high Arctic
807 marine food web using $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis. *Marine Ecology Progress Series*, 84(1):
808 9-18.

809 Hobson, K.A., Ambrose Jr, W.G. and Renaud, P.E. 1995. Sources of primary production,
810 benthic-pelagic coupling, and trophic relationships within the Northeast Water Polynya:
811 insights from $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis. *Marine Ecology Progress Series*, 128: 1-10.

812 Hobson, K.A., Van Wilgenburg, S.L., Wassenaar, L.I. and Larson, K. 2012. Linking hydrogen
813 ($\delta^2\text{H}$) isotopes in feathers and precipitation: sources of variance and consequences for
814 assignment to isoscapes. *PloS one*, 7(4): p.e35137.

815 Hobson, K.A., L.K. Blight and P. Arcese. 2015. Human-induced long-term shifts in gull diet
816 from marine to terrestrial sources in North America's coastal Pacific: More evidence from
817 more isotopes ($\delta^2\text{H}$, $\delta^{34}\text{S}$). *Environmental Science and Technology* 49 :10834–10840.
818

819 IPCC 2019: Climate Change and Land: an IPCC special report on climate change,
820 desertification, land degradation, sustainable land management, food security, and
821 greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia,
822 V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van
823 Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal
824 Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

825 Inger, R. and Bearhop, S. 2008. Applications of stable isotope analyses to avian ecology. *Ibis*,
826 150(3): 447-461.

827 Jackson, M.C., Woodford, D.J., Bellingan, T.A., Weyl, O.L., Potgieter, M.J., Rivers-Moore,
828 N.A., Ellender, B.R., Fourie, H.E. and Chimimba, C.T. 2016. Trophic overlap between
829 fish and riparian spiders: potential impacts of an invasive fish on terrestrial consumers.
830 *Ecology and Evolution*, 6(6): 1745-1752.

831 Jakubas, D., Wojczulanis-Jakubas, K., Iliszko, L.M., Strøm, H. and Stempniewicz, L. 2017.
832 Habitat foraging niche of a High Arctic zooplanktivorous seabird in a changing
833 environment. *Scientific Reports*, 7(1): 1-14.

834 Johannessen, O.M., Bengtsson, L., Miles, M.W., Kuzmina, S.I., Semenov, V.A., Alekseev, G.V.,
835 Nagurnyi, A.P., Zakharov, V.F., Bobylev, L.P., Pettersson, L.H. and Hasselmann, K.
836 2004. Arctic climate change: observed and modelled temperature and sea-ice variability.
837 *Tellus A: Dynamic Meteorology and Oceanography*, 56(4): 28-341.

838 Jónsson, J.E., Gardarsson, A., Gill, J.A., Pétursdóttir, U.K., Petersen, A. and Gunnarsson, T.G.
839 2013. Relationships between long-term demography and weather in a sub-arctic
840 population of common eider. PLoS one, 8(6): e67093.

841 Karnovsky, N.J., Hobson, K.A., Iverson, S. and Hunt Jr, G.L. 2008. Seasonal changes in diets of
842 seabirds in the North Water Polynya: a multiple-indicator approach. Marine Ecology
843 Progress Series, 357: 291-299.

844 Kirk, J.L., Lehnerr, I., Andersson, M., Braune, B.M., Chan, L., Dastoor, A.P., Durnford, D.,
845 Gleason, A.L., Loseto, L.L., Steffen, A. and Louis, V.L.S. 2012. Mercury in Arctic
846 marine ecosystems: Sources, pathways and exposure. Environmental Research, 119: 64-
847 87.

848 Kohlbach, D., Graeve, M., A. Lange, B., David, C., Peeken, I. and Flores, H. 2016. The
849 importance of ice algae-produced carbon in the central Arctic Ocean ecosystem: Food
850 web relationships revealed by lipid and stable isotope analyses. Limnology and
851 Oceanography, 61(6): 2027-2044.

852 Kristjánsson, T.Ö., Jónsson, J.E. and Svavarsson, J. 2013. Spring diet of common eiders
853 (*Somateria mollissima*) in Breiðafjörður, West Iceland, indicates non-bivalve
854 preferences. Polar Biology, 36(1), 51-59.

855 Laursen, K., Moller, A., and Hobson, K.A. 2018. N-isotopes in feathers and abundance of eiders
856 respond to nutrients in seawater. Ecosystems, 22: 1271–1279.

857 Le Bohec, C., Whittington, J.D. and Le Maho, Y. 2013. Polar monitoring: seabirds as sentinels
858 of marine ecosystems. In Adaptation and Evolution in Marine Environments, Volume 2
859 (205-230). Springer, Berlin, Heidelberg.

860 Le Croizier, G., Schaal, G., Point, D., Le Loc'h, F., Machu, E., Fall, M., Munaron, J.M., Boyé,
861 A., Walter, P., Laë, R. and De Morais, L.T. 2019. Stable isotope analyses revealed the
862 influence of foraging habitat on mercury accumulation in tropical coastal marine
863 fish. *Science of the Total Environment*, 650: 2129-2140.

864 Lemons, G.E., Eguchi, T., Lyon, B.N., LeRoux, R. and Seminoff, J.A. 2012. Effects of blood
865 anticoagulants on stable isotope values of sea turtle blood tissue. *Aquatic Biology*, 14(3):
866 201-206.

867 Leu, E., Søreide, J.E., Hessen, D.O., Falk-Petersen, S. and Berge, J. 2011. Consequences of
868 changing sea-ice cover for primary and secondary producers in the European Arctic shelf
869 seas: timing, quantity, and quality. *Progress in Oceanography*, 90(1-4): 18-32.

870 Lewis, K.M., van Dijken, G.L. and Arrigo, K.R. 2020. Changes in phytoplankton concentration
871 now drive increased Arctic Ocean primary production. *Science*, 369(6500): 198-202.

872 Liu, G., Cai, Y., O'Driscoll, N., Feng, X. and Jiang, G. 2012. Overview of mercury in the
873 environment. *Environmental Chemistry and Toxicology of Mercury*, 1-12.

874 Ma, N.L., Hansen, M., Therkildsen, O.R., Christensen, T.K., Tjørnløv, R.S., Garbus, S.E.,
875 Lyngs, P., Peng, W., Lam, S.S., Krogh, A.K.H. and Andersen-Ranberg, E. 2020. Body
876 mass, mercury exposure, biochemistry and untargeted metabolomics of incubating
877 common eiders (*Somateria mollissima*) in three Baltic colonies. *Environment*
878 *International*, 142: 105866.

879 Macdonald, R.W., Barrie, L.A., Bidleman, T.F., Diamond, M.L., Gregor, D.J., Semkin, R.G.,
880 Strachan, W.M.J., Li, Y.F., Wania, F., Alae, M. and Alexeeva, L.B. 2000. Contaminants
881 in the Canadian Arctic: 5 years of progress in understanding sources, occurrence and
882 pathways. *Science of the Total Environment*, 254(2-3): 93-234.

883 Macdonald, R.W., Harner, T. and Fyfe, J. 2005. Recent climate change in the Arctic and its
884 impact on contaminant pathways and interpretation of temporal trend data. *Science of the*
885 *Total Environment*, 342(1-3): 5-86.

886 Mallory, M.L., Braune, B.M., Wayland, M., Gilchrist, H.G. and Dickson, D.L. 2004.
887 Contaminants in common eiders (*Somateria mollissima*) of the Canadian Arctic.
888 *Environmental Reviews*, 12: 197-218.

889 Mallory, M.L. and Braune, B.M. 2012. Tracking contaminants in seabirds of Arctic Canada:
890 temporal and spatial insights. *Marine Pollution Bulletin*, 64(7): 1475-1484.

891 Mallory, C.D., Gilchrist, H.G., Robertson, G.J., Provencher, J.F., Braune, B.M., Forbes, M.R.
892 and Mallory, M.L. 2017. Hepatic trace element concentrations of breeding female
893 common eiders across a latitudinal gradient in the eastern Canadian Arctic. *Marine*
894 *Pollution Bulletin*, 124(1): 252-257.

895 Mallory, M.L., Ronconi, R.A., Allen, R.B., Dwyer, C., Lair, S., Mallory, C.D., McLellan, N.R.,
896 Milton, G.R., Parsons, G.J., Savoy, L. and Tomlik, M.D. 2020. Annual movement
897 patterns of American common eiders *Somateria mollissima dresseri*. *Wildlife*
898 *Biology*, 2020(2).

899 McKinney, M.A., Pedro, S., Dietz, R., Sonne, C., Fisk, A.T., Roy, D., Jenssen, B.M. and
900 Letcher, R.J. 2015. A review of ecological impacts of global climate change on persistent
901 organic pollutant and mercury pathways and exposures in arctic marine ecosystems.
902 *Current Zoology*, 61(4): 617-628.

903 McMahon, K.W., Ambrose Jr, W.G., Johnson, B.J., Sun, M.Y., Lopez, G.R., Clough, L.M. and
904 Carroll, M.L. 2006. Benthic community response to ice algae and phytoplankton in Ny
905 Ålesund, Svalbard. *Marine Ecology Progress Series*, 310: 1-14.

906 McMahon, K.W., Hamady, L.L. and Thorrold, S.R. 2013. A review of ecogeochemistry
907 approaches to estimating movements of marine animals. *Limnology and Oceanography*,
908 58(2): 697-714.

909 Milton, G.R., Iverson, S.A., Smith, P.A., Tomlik, M.D., Parsons, G.J., and Mallory, M.L. 2016.
910 Sex-Specific Survival of Adult Common Eiders in Nova Scotia, Canada. *The Journal of*
911 *Wildlife Management*, 80(8): 1427-1436.

912 Moline, M.A., Karnovsky, N.J., Brown, Z., Divoky, G.J., Frazer, T.K., Jacoby, C.A., Torres, J.J.
913 and Fraser, W.R. 2008. High latitude changes in ice dynamics and their impact on polar
914 marine ecosystems. *Annals of the New York Academy of Sciences*, 1134: 267-319.

915 Mouritsen, K.N., Tompkins, D.M. and Poulin, R. 2005. Climate warming may cause a parasite-
916 induced collapse in coastal amphipod populations. *Oecologia*, 146(3): 476-483.

917 Muir, D., Braune, B., DeMarch, B., Norstrom, R., Wagemann, R., Lockhart, L., Hargrave, B.,
918 Bright, D., Addison, R., Payne, J. and Reimer, K. 1999. Spatial and temporal trends and
919 effects of contaminants in the Canadian Arctic marine ecosystem: a review. *Science of*
920 *the Total Environment*, 230(1-3): 83-144.

921 Najafi, M.R., Zwiers, F.W., and Gillett, N.P. 2015. Attribution of Arctic temperature change to
922 greenhouse-gas and aerosol influences. *Nature Climate Change*, 5(3): 246-249.

923 Nakashima, D.J. and Murray, D.J. 1988. The common eider (*Somateria mollissima sedentaria*)
924 of eastern Hudson Bay: A survey of nest colonies and Inuit ecological knowledge.
925 Environmental Studies Research Funds.

926 Newsome, S.D., Martinez del Rio, C., Bearhop, S. and Phillips, D.L. 2007. A niche for isotopic
927 ecology. *Frontiers in Ecology and the Environment*, 5(8): 429-436.

928 Noel, K., McLellan, N., Gilliland, S., Allard, K.A., Allen, B., Craik, S., Demagny, A., English,
929 M.D., Diamond, A., Giroux, J.F., Hanson, A., Heusmann, H.W., King, L.E., Lepage, C.,
930 Major, H., AcAuley, D., Meattey, D.E., Milton, G.R., Osenkowski, J., Roberts, A.,
931 Robertson, G.J., Roy, M., Savoy, L., Sullivan, K., and Mallory, M.L. 2021. Expert
932 opinion on American common eiders in eastern North America: international information
933 needs for future conservation. *Socio-Ecological Practice Research*, 1-14.

934 O'Donovan, S., S. Budge, K.A. Hobson, A. Kelly, and A. Derocher. 2018. Intrapopulation
935 variability in wolf diet revealed using a combined stable isotope and fatty acid approach.
936 *Ecosphere*, 9(9):e02420. 10.1002/ecs2.2420.

937
938 Paredes, R., Harding, A.M., Irons, D.B., Roby, D.D., Suryan, R.M., Orben, R.A., Renner, H.,
939 Young, R. and Kitaysky, A. 2012. Proximity to multiple foraging habitats enhances
940 seabirds' resilience to local food shortages. *Marine Ecology Progress Series*, 471: 253-
941 269.

942 Paris, O.J., Swaddle, J.P. and Cristol, D.A. 2018. Exposure to dietary methyl-mercury solely
943 during embryonic and juvenile development halves subsequent reproductive success in
944 adult zebra finches. *Environmental Science and Technology*, 52(5): 3117-3124.

945 Parkinson, K.J.L. 2020. Using isotopic niche dynamics to predict resiliency to climate change in
946 an Arctic seabird. *Electronic Theses and Dissertations*. 8336.

947 Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annual*
948 *Review of Ecology, Evolution, and Systematics*, 37: 637-669.

949 Pecuchet, L., Blanchet, M.A., Frainer, A., Husson, B., Jørgensen, L.L., Kortsch, S. and
950 Primicerio, R. 2020. Novel feeding interactions amplify the impact of species
951 redistribution on an Arctic food web. *Global Change Biology*, 26(9): 4894-4906.

952 Pomerleau, C., Stern, G.A., Pućko, M., Foster, K.L., Macdonald, R.W. and Fortier, L. 2016. Pan-
953 Arctic concentrations of mercury and stable isotope ratios of carbon ($\delta^{13}\text{C}$) and nitrogen
954 ($\delta^{15}\text{N}$) in marine zooplankton. *Science of the Total Environment*, 551: 92-100.

955 Post, E. 2017. Implications of earlier sea ice melt for phenological cascades in arctic marine food
956 webs. *Food Webs*, 13: 60-66.

957 Post, E., Bhatt, U.S., Bitz, C.M., Brodie, J.F., Fulton, T.L., Hebblewhite, M., Kerby, J., Kutz,
958 S.J., Stirling, I. and Walker, D.A. 2013. Ecological consequences of sea-ice decline.
959 *Science*, 341(6145): 519-524.

960 Pratte, I., Braune, B.M., Hobson, K.A. and Mallory, M.L. 2019. Variable sea-ice conditions
961 influence trophic dynamics in an Arctic community of marine top predators. *Ecology and*
962 *Evolution*, 9(13): 7639-7651.

963 Priest, H., and Usher, P.J. 2004. The Nunavut wildlife harvest study. August 2004, p.822.
964 Nunavut Wildlife Management Board, Iqaluit, Nunavut.

965 Provencher, J.F., Forbes, M.R., Hennin, H.L., Love, O.P., Braune, B.M., Mallory, M.L. and
966 Gilchrist, H.G. 2016. Implications of mercury and lead concentrations on breeding
967 physiology and phenology in an Arctic bird. *Environmental Pollution*, 218: 1014-1022.

968 Purwandana, D., Ariefiandy, A., Imansyah, M.J., Seno, A., Ciofi, C., Letnic, M. and Jessop, T.S.
969 2016. Ecological allometries and niche use dynamics across Komodo dragon ontogeny.
970 *The Science of Nature*, 103(3-4): 27.

971 Rabosky, D.L. 2009. Ecological limits and diversification rate: alternative paradigms to explain
972 the variation in species richness among clades and regions. *Ecology Letters*, 12(8): 735-
973 743.

974 Ramos, R. and González-Solís, J. 2012. Trace me if you can: the use of intrinsic biogeochemical
975 markers in marine top predators. *Frontiers in Ecology and the Environment*, 10(5): 258-
976 266.

977 Renaut, S., Devred, E. and Babin, M, 2018. Northward expansion and intensification of
978 phytoplankton growth during the early ice-free season in Arctic. *Geophysical Research*
979 *Letters*, 45(19): 10590-10598.

980 Renedo, M., Amouroux, D., Albert, C., Bérail, S., Bråthen, V.S., Gavrilo, M., Grémillet, D.,
981 Helgason, H.H., Jakubas, D., Mosbech, A., Strøm, H., Tessier, E., Wojczulanis-Kakubas,
982 K., Bustamante, P., and Fort, J. 2020. Contrasting spatial and seasonal trends of
983 methylmercury exposure pathways of Arctic seabirds: combination of large-scale
984 tracking and stable isotopic approaches. *Environmental Science and Technology*, 54(21):
985 13619-13629.

986 Rimmer, C.C., McFarland, K.P., Evers, D.C., Miller, E.K., Aubry, Y., Busby, D. and Taylor, R.J.
987 2005. Hg concentrations in Bicknell's thrush and other insectivorous passerines in
988 montane forests of northeastern North America. *Ecotoxicology*, 14(1-2): 223-240.

989 Rutkowska, M., Bajger-Nowak, G., Kowalewska, D., Bzoma, S., Kalisińska, E., Namieśnik, J.
990 and Konieczka, P. 2019. Methylmercury and total mercury content in soft tissues of two
991 bird species wintering in the Baltic Sea near Gdansk, Poland. *Chemosphere*, 219: 140-
992 147.

993 Rydberg, J., Klaminder, J., Rosén, P. and Bindler, R. 2010. Climate driven release of carbon and
994 mercury from permafrost mires increases mercury loading to sub-arctic lakes. *Science of*
995 *the Total Environment*, 408(20): 4778-4783.

996 Sackett, W.M., Eckelmann, W.R., Bender, M.L. and Bé, A.W. 1965. Temperature dependence of
997 carbon isotope composition in marine plankton and sediments. *Science*, 148(3667): 235-
998 237.

999 Sarà, G., De Pirro, M., Romano, C., Rumolo, P., Sprovieri, M. and Mazzola, A. 2007. Sources of
1000 organic matter for intertidal consumers on Ascophyllum-shores (SW Iceland): a multi-
1001 stable isotope approach. *Helgoland Marine Research*, 61(4): 297-302.

1002 Savoy, L., Flint, P., Zwiefelhofer, D., Brant, H., Perkins, C., Taylor, R., Lane, O., Hall, J., Evers,
1003 D. and Schamber, J. 2017. Geographic and temporal patterns of variation in total mercury
1004 concentrations in blood of harlequin ducks and blue mussels from Alaska. *Marine*
1005 *Pollution Bulletin*, 117(1-2): 178-183.

1006 Schamel, D., 1977. Breeding of the common eider (*Somateria mollissima*) on the Beaufort Sea
1007 coast of Alaska. *The Condor*, 79(4): 478-485.

1008 Scheuhammer, A., Braune, B., Chan, H.M., Frouin, H., Krey, A., Letcher, R., Loseto, L., Noël,
1009 M., Ostertag, S., Ross, P. and Wayland, M. 2015. Recent progress on our understanding
1010 of the biological effects of mercury in fish and wildlife in the Canadian Arctic. *Science of*
1011 *the Total Environment*, 509: 91-103.

1012 Schoch, N., Glennon, M.J., Evers, D.C., Duron, M., Jackson, A.K., Driscoll, C.T., Ozard, J.W.
1013 and Sauer, A.K. 2014. The impact of mercury exposure on the Common Loon (*Gavia*
1014 *immer*) population in the Adirondack Park, New York, USA. *Waterbirds*, 37(sp1): 133-
1015 146.

1016 Schuster, P.F., Schaefer, K.M., Aiken, G.R., Antweiler, R.C., Dewild, J.F., Gryziec, J.D.,
1017 Gusmeroli, A., Hugelius, G., Jafarov, E., Krabbenhoft, D.P. and Liu, L. 2018. Permafrost

1018 stores a globally significant amount of mercury. *Geophysical Research Letters*, 45(3):
1019 1463-1471.

1020 Screen, J.A. and Simmonds, I. 2010. Increasing fall-winter energy loss from the Arctic Ocean
1021 and its role in Arctic temperature amplification. *Geophysical Research Letters*, 37(16).

1022 Sénéchal, É., Bêty, J., Gilchrist, H.G., Hobson, K.A. and Jamieson, S.E. 2011. Do purely capital
1023 layers exist among flying birds? Evidence of exogenous contribution to arctic-nesting
1024 common eider eggs. *Oecologia*, 165(3): 593-604.

1025 Smith, B.D. and Reeves, R.R. 2012. River cetaceans and habitat change: generalist resilience or
1026 specialist vulnerability? *Journal of Marine Biology*, 2012: 1-11.

1027 Smith, V.H., Tilman, G.D. and Nekola, J.C. 1999. Eutrophication: impacts of excess nutrient
1028 inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, 100(1-
1029 3): 179-196.

1030 Søreide, J.E., Tamelander, T., Hop, H., Hobson, K.A. and Johansen, I. 2006. Sample preparation
1031 effects on stable C and N isotope values: a comparison of methods in Arctic marine food
1032 web studies. *Marine Ecology Progress Series*, 328: 17-28.

1033 Søreide, J.E., Carroll, M.L., Hop, H., Ambrose Jr, W.G., Hegseth, E.N. and Falk-Petersen, S.,
1034 2013. Sympagic-pelagic-benthic coupling in Arctic and Atlantic waters around Svalbard
1035 revealed by stable isotopic and fatty acid tracers. *Marine Biology Research*, 9(9): 831-
1036 850.

1037 Soerensen, A. L.; Jacob, D. J.; Schartup, A. T.; Fisher, J. A.; Lehnerr, I.; St. Louis, V. L.;
1038 Heimbürger, L.-E.; Sonke, J. E.; Krabbenhoft, D. P.; Sunderland, E. M. 2016. A mass
1039 budget for mercury and methylmercury in the Arctic Ocean. *Global Biogeochemical*
1040 *Cycles* 30 (4), 560–575.

1041
1042 Staudinger, M.D., Mills, K.E., Stamieszkin, K., Record, N.R., Hudak, C.A., Allyn, A., Diamond,
1043 A., Friedland, K.D., Golet, W., Henderson, M.E. and Hernandez, C.M. 2019. It's about
1044 time: a synthesis of changing phenology in the Gulf of Maine ecosystem. *Fisheries*
1045 *Oceanography*, 28(5): 532-566.

1046 Steenweg, R.J., Crossin, G.T., Kyser, T.K., Merkel, F.R., Gilchrist, H.G., Hennin, H.L.,
1047 Robertson, G.J., Provencher, J.F., Mills Flemming, J. and Love, O.P. 2017. Stable
1048 isotopes can be used to infer the overwintering locations of prebreeding marine birds in
1049 the Canadian Arctic. *Ecology and Evolution*, 7(21): 8742-8752.

1050 Stern, G.A., Macdonald, R.W., Outridge, P.M., Wilson, S., Chetelat, J., Cole, A., Hintelmann,
1051 H., Loseto, L.L., Steffen, A., Wang, F. and Zdanowicz, C. 2012. How does climate
1052 change influence arctic mercury? *Science of the Total Environment*, 414: 22-42.

1053 Sunderland, E.M. and Mason, R.P. 2007. Human impacts on open ocean mercury concentrations.
1054 *Global Biogeochemical Cycles*, 21(4).

1055 Swanson, H.K., Lysy, M., Power, M., Stasko, A.D., Johnson, J.D. and Reist, J.D. 2015. A new
1056 probabilistic method for quantifying n-dimensional ecological niches and niche overlap.
1057 *Ecology*, 96(2): 318-324.

1058 Swart, N.C., Fyfe, J.C., Hawkins, E., Kay, J.E. and Jahn, A. 2015. Influence of internal
1059 variability on Arctic sea-ice trends. *Nature Climate Change*, 5(2): 86-89.

1060 Sydeman, W.J., Thompson, S.A. and Kitaysky, A. 2012. Seabirds and climate change: roadmap
1061 for the future. *Marine Ecology Progress Series*, 454: 107-117.

1062 Tamelander, T., Renaud, P.E., Hop, H., Carroll, M.L., Ambrose Jr, W.G. and Hobson, K.A.
1063 2006. Trophic relationships and pelagic–benthic coupling during summer in the Barents

1064 Sea Marginal Ice Zone, revealed by stable carbon and nitrogen isotope
1065 measurements. *Marine Ecology Progress Series*, 310: 33-46.

1066 Tamelander, T., Kivimäe, C., Bellerby, R.G., Renaud, P.E. and Kristiansen, S. 2009. Base-line
1067 variations in stable isotope values in an Arctic marine ecosystem: effects of carbon and
1068 nitrogen uptake by phytoplankton. *Hydrobiologia*, 630(1): 63-73.

1069 Tartu, S., Goutte, A., Bustamante, P., Angelier, F., Moe, B., Clément-Chastel, C., Bech, C.,
1070 Gabrielsen, G.W., Bustnes, J.O. and Chastel, O. 2013. To breed or not to breed:
1071 endocrine response to mercury contamination by an Arctic seabird. *Biology Letters*, 9(4):
1072 20130317.

1073 Timmermans, M.L., Proshutinsky, A., Krishfield, R.A., Perovich, D.K., Richter-Menge, J.A.,
1074 Stanton, T.P., and Toole, J.M. 2011. Surface freshening in the Arctic Ocean's Eurasian
1075 Basin: An apparent consequence of recent change in the wind-driven circulation. *Journal*
1076 *of Geophysical Research: Oceans*, 116(C8).

1077 Vander Zanden, M.J., Cabana, G. and Rasmussen, J.B. 1997. Comparing trophic position of
1078 freshwater fish calculated using stable nitrogen isotope ratios ($\delta^{15}\text{N}$) and literature dietary
1079 data. *Canadian Journal of Fisheries and Aquatic Sciences*, 54(5): 1142-1158.

1080 Vander Zanden, M.J. and Rasmussen, J.B. 1999. Primary consumer $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ and the
1081 trophic position of aquatic consumers. *Ecology*, 80(4): 1395-1404.

1082 Vander Zanden, H.B., Bjorndal, K.A., Reich, K.J. and Bolten, A.B. 2010. Individual specialists
1083 in a generalist population: results from a long-term stable isotope series. *Biology Letters*,
1084 6(5): 711-714.

1085 Vasseur, D.A. and McCann, K.S. 2005. A mechanistic approach for modeling temperature-
1086 dependent consumer-resource dynamics. *The American Naturalist*, 166(2): 184-198.

1087 Vieweg, I., Hop, H., Brey, T., Huber, S., Ambrose Jr, W.G. and Gabrielsen, G.W. 2012.
1088 Persistent organic pollutants in four bivalve species from Svalbard waters. *Environmental*
1089 *Pollution*, 161: 134-142.

1090 Vincent, W.F. 2010. Microbial ecosystem responses to rapid climate change in the Arctic. *The*
1091 *ISME Journal*, 4(9): 1087-1090.

1092 Waltho, C. and Coulson, J. 2015. *The Common Eider* (Vol. 35). Bloomsbury Publishing.

1093 Wayland, M., Gilchrist, H.G. and Neugebauer, E. 2005. Concentrations of cadmium, mercury
1094 and selenium in common eider ducks in the eastern Canadian arctic: influence of
1095 reproductive stage. *Science of the Total Environment*, 351: 323-332.

1096 Werner, I. 1997. Grazing of Arctic under-ice amphipods on sea-ice algae. *Marine Ecology*
1097 *Progress Series*, 160: 93-99.

1098 Whitney, M.C. and Cristol, D.A. 2017. Impacts of sublethal mercury exposure on birds: a
1099 detailed review. In *Reviews of Environmental Contamination and Toxicology* (113-163).
1100 Springer, Cham.

1101 Wiener, J.G., Krabbenhoft, D.P., Heinz, G.H. and Scheuhammer, A.M. 2003. Ecotoxicology of
1102 mercury. *Handbook of Ecotoxicology*, 2: 409-463.

1103 Wolf, N., Carleton, S.A. and del Rio, C.M. 2009. Ten years of experimental animal isotopic
1104 ecology. *Functional Ecology*, 23(1): 17-26.

1105 Woo, K.J., Elliott, K.H., Davidson, M., Gaston, A.J. and Davoren, G.K. 2008. Individual
1106 specialization in diet by a generalist marine predator reflects specialization in foraging
1107 behaviour. *Journal of Animal Ecology*, 77(6): 1082-1091.

1108 Yakovis, E.L., Artemieva, A.V., Fokin, M.V. and Varfolomeeva, M.A. 2012. Intraspecific
1109 variation in stable isotope signatures indicates no small-scale feeding interference
1110 between a horse mussel and an ascidian. *Marine Ecology Progress Series*, 467: 113-120.

1111 Yurkowski, D.J., Ferguson, S., Choy, E.S., Loseto, L.L., Brown, T.M., Muir, D.C., Semeniuk,
1112 C.A. and Fisk, A.T. 2016. Latitudinal variation in ecological opportunity and
1113 intraspecific competition indicates differences in niche variability and diet specialization
1114 of Arctic marine predators. *Ecology and Evolution*, 6(6): 1666-1678.

1115 Yurkowski, D.J., Brown, T.A., Blanchfield, P.J., Ferguson, S.H. 2020a. Atlantic walrus signal
1116 latitudinal differences in the long-term decline of sea ice-derived carbon to benthic fauna
1117 in the Canadian Arctic. *Proceedings of the Royal Society B: Biological Sciences*,
1118 287(1940): 20202126.

1119 Yurkowski, D.J., Richardson, E.S., Lunn, N.J., Muir, D.C., Johnson, A.C., Derocher, A.E.,
1120 Ehrman, A.D., Houde, M., Young, B.G., Debets, C.D. and Sciullo, L. 2020b. Contrasting
1121 Temporal Patterns of Mercury, Niche Dynamics, and Body Fat Indices of Polar Bears
1122 and Ringed Seals in a Melting Icescape. *Environmental Science and Technology*, 54(5):
1123 2780-2789.

1124 Zhang, J. 2005. Warming of the arctic ice-ocean system is faster than the global average since
1125 the 1960s. *Geophysical Research Letters*, 32(19).

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.

| Location | n | Sampling month | Latitude | Longitude | Migratory behaviour | Sea ice cover |
|----------------------------------|----------|-----------------------|-----------------|------------------|----------------------------|----------------------|
| 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 |

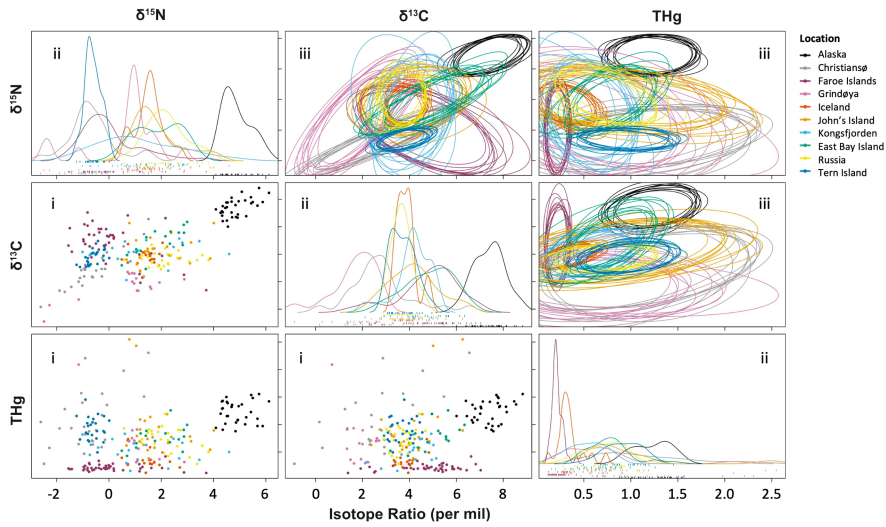
1138

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 (β) | SE | df | t | p |
|---|----------------------|-------|---------|--------|------------------|
| a) 2-tailed t-test – Migratory Status | | | | | |
| 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 |
| Individual $\delta^{13}\text{C}$ | | | 238 | 2.218 | 0.028 |
| Individual $\delta^{15}\text{N}$ | | | 220 | -6.858 | <0.001 |
| log(Individual THg) | | | 124 | -6.329 | <0.001 |
| b) GLM – Sea Ice Cover | | | | | |
| 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 |
| log(Median $\delta^{13}\text{C}$) | 0.028 | 0.010 | 8 | 2.936 | 0.032 |
| Median $\delta^{15}\text{N}$ | 0.052 | 0.022 | 8 | 2.332 | 0.048 |
| log(Median THg) | 0.014 | 0.006 | 8 | 2.525 | 0.036 |
| c) GLMM – Individual log(THg) | | | | | |
| Intercept | -1.923 | 0.304 | 142.233 | -6.330 | <0.0001 |
| Trophic position | 0.563 | 0.096 | 234.614 | 5.862 | <0.001 |
| $\delta^{13}\text{C}$ | -0.063 | 0.022 | 232.943 | -2.813 | 0.005 |

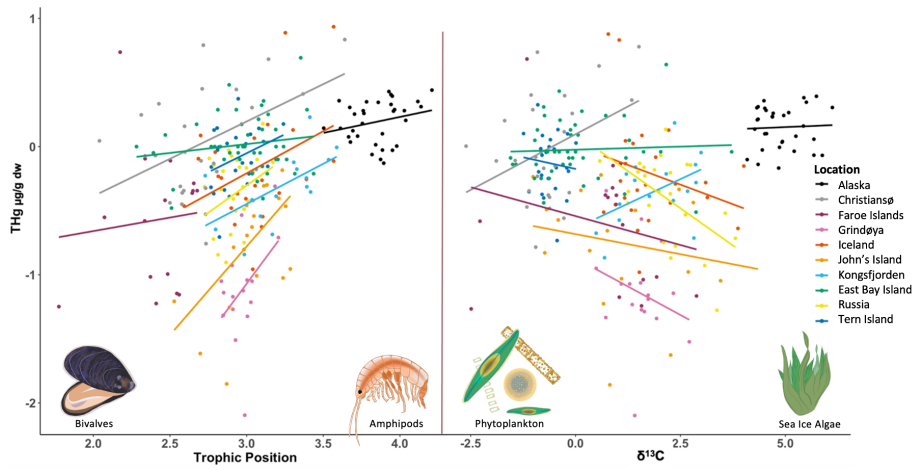


1146
 1147 **Figure 1.** Map of the circumpolar-Arctic, and locations of the 10 common eider colonies used in
 1148 this study (stars) designated by whether a colony is primarily resident (circles) or migratory
 1149 (squares). Shape colour represents four groupings of similar median 3-dimensional niche 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).



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**

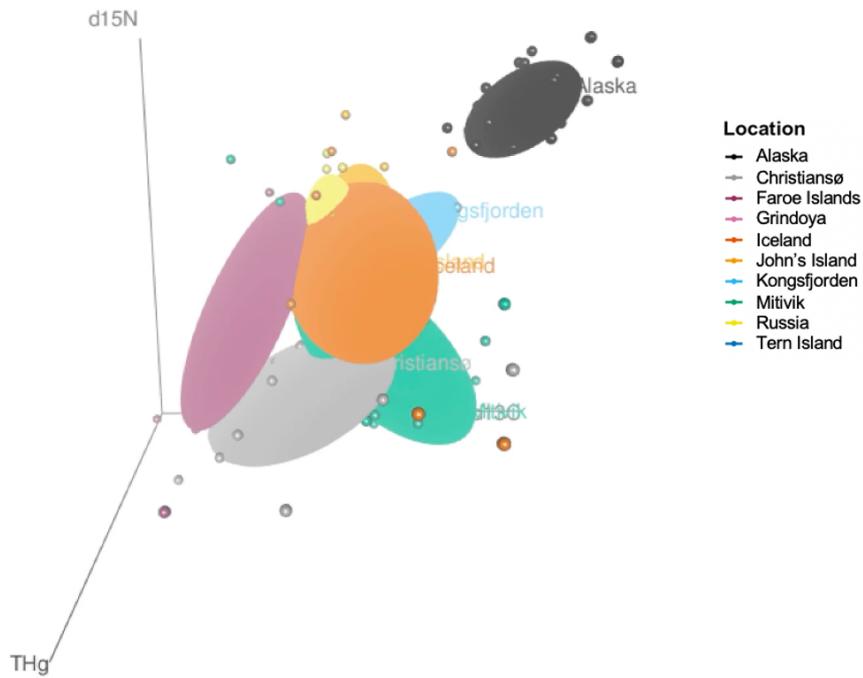
1167 Sample sizes (n), means \pm SD, Min-Max (in %) for $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and total Hg (THg in $\mu\text{g/g dw}$)
 1168 (values in brackets corrected for colony baseline ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) and standardized for units ($\delta^{13}\text{C}$,
 1169 $\delta^{15}\text{N}$ 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 |

1172

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 $\mu\text{g/g dw}$) 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).