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Contaminants in indigenous harvests of apex predators: The Tasmanian Short-tailed Shearwater as a case study

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ABSTRACT

The Short-tailed Shearwater (*Puffinus tenuirostris*), or muttonbird, migrates between hemispheres and is subject to an annual harvest at its breeding grounds in Tasmania. As top predators, these seabirds are exposed to high concentrations of contaminants. Concentrations of total polychlorinated biphenyls (PCBs) and 22 elements were determined in Short-tailed Shearwater muscle to evaluate the safety of this meat product for human consumption. Among muscle samples, 57 per cent exceeded food safety standards for either lead (>0.10 μg/g wet weight (ww)) or copper (>0.01 μg/g ww/kg body mass). All muscle samples had total PCB concentrations below the limit of detection (<0.01 μg/g ww). We also sampled feathers to investigate their utility in predicting internal contaminant burdens. Feather-muscle relationships among elements were generally poor, especially for toxicologically important elements (As, Cd, Hg, Pb), limiting the utility of feathers to monitor internal contaminant concentrations. There are no existing monitoring programs for contaminants in harvested wild birds in Australia, and we urge a greater integration between human and wildlife health studies, especially in remote areas where harvesting wildlife is more prevalent, culturally important, and forms a significant component of human diets.

1. Introduction

The Short-tailed Shearwater (*Puffinus tenuirostris*), or Tasmanian muttonbird, is a highly migratory seabird ranging from the North Pacific Ocean in the non-breeding season to key foraging areas in Antarctic waters during the breeding season in the Austral summer (Woehler et al., 2006). Breeding colonies are confined to southern Australia, with 75 per cent of the population (approx. eighteen million individuals) breeding in more than 200 rookeries on offshore islands and headlands in Tasmania (Skira, 1996). Due to their great abundance, harvesting of Short-tailed Shearwaters has been a traditional activity undertaken in March/April each year since at least the 1820s (Callister, 1991; DPIPWE, 2010a; Hill et al., 1981). There is an indigenous commercial harvest for meat, feathers and oil on several islands in the Furneaux group in north-east Tasmania, and a recreational harvest open to the public and subject to a permit system in a subset of rookeries in the Furneaux and Hunter Island groups, as well as King Island in the northwest, and along Tasmania's west coast (Fig. 1; DPIPWE, 2010a).

In the past, up to a million Short-tailed Shearwater adults, eggs, and chicks were harvested annually (Skira et al., 1985). However, the introduction of a set harvest season, banning the take of adult birds and eggs, introduction of a state-wide licensing system in 1990, and lowered bag limits, has reduced the number of chicks harvested in recent years (DPIPWE, 2010b). In 2009, the Tasmanian recreational harvest was 49,800 chicks from 32 colonies (DPIPWE, 2010b) with a further 65,000 chicks taken in the indigenous and cultural harvests (DPIPWE, 2010a, 2010b). However, an unknown number of birds are taken by poachers each year, and may double the annual reported harvest (Callister, 1991). Despite the low harvesting pressure in relation to total population size, the Short-tailed Shearwater was recently identified as a priority for monitoring due to exceptionally low burrow occupancy rates (5–22 per cent) and documented population declines at some colonies (DPIPWE, 2010b; Driessen and Hocking, 2008; Vertigan, 2010). As a result, harvesting at some rookeries is prohibited in some years (DPIPWE, 2010b).

Short-tailed Shearwaters are among the top predators in the North Pacific and southern Australian marine ecosystems (Vlietstra et al., 2005). Due to their relatively high trophic position, they are at risk from the bioaccumulation of toxic metals and

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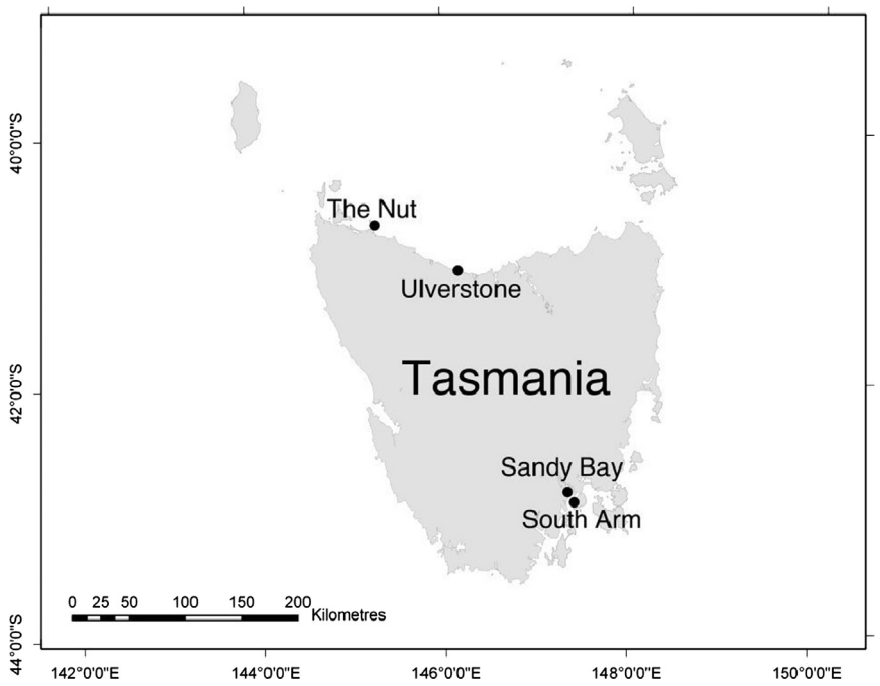

Fig. 1. We analysed contaminants in Tasmanian Short-tailed Shearwater chick breast muscle collected at The Nut Reserve ($n=10$), Ulverstone ($n=1$), and from locations around southeast Tasmania ($n=3$).

persistent organic pollutants like polychlorinated biphenyls (PCBs) from numerous sources (Braune and Simon, 2003; Honda et al., 1990). Non-essential elements such as mercury (Hg), lead (Pb), cadmium (Cd), and arsenic (As) are transported atmospherically around the globe (Nriagu, 1989) and cause deleterious health effects in both human and wildlife populations (Burger and Gochfeld, 2002; Sweet and Zelikoff, 2001; Wolfe et al., 2009). Current Australian food standard guidelines for meat limit Hg, Pb, Cd, and As to 0.50, 0.10, 0.05, and 1.00 μg/g wet weight, respectively (Department of Health and Ageing, 2011). Recommendations for acute and intermediate exposure to oral doses of copper (Cu) are 0.01 mg/kg body mass/day (ATSDR, 2004). In 1992, Hg concentrations in liver[1] tissue from Short-tailed Shearwaters taken as bycatch in North Pacific fisheries were above the limit at 0.75 μg/g ww (assuming 67 per cent moisture content, see below; Elliott, 2005). The effects of these contaminants on the health of humans who consume these birds are not known. As the provenance of birds utilised in previous studies was not known, an analysis of contemporary samples collected from currently exploited Tasmanian colonies was undertaken to assess the risk posed to human health through the consumption of Short-tailed Shearwater meat. We also examined the relationship in trace element concentrations between paired breast feathers and muscle, as feathers are more easily collected, and transported, and because chicks' feathers would be grown at the same time as the muscle was formed.

2. Methods

2.1. Sample collection and study area

We collected five breast feathers and corresponding breast muscle samples from fourteen Short-tailed Shearwater chicks (approx. 80 days old). Of these, ten were confiscated in The Nut State Reserve in northwest Tasmania in April 2011 (40°45′S, 145°17′E). Muscle from three other chicks was sampled from southeast Tasmania (Sandy Bay 42°54′S, 147°19′E; South Arm 43°01′S, 147°24′E), and one from northern Tasmania (Ulverstone 41°08′S, 146°09′E; Fig. 1). Sampling locations and sample size were chosen based on the availability of fresh, intact carcasses. We sampled feathers because the stability of this tissue lends itself to storage and transport, they can be more readily collected from beach-cast birds and harvesting sheds, and breast and secondary coverts are the best indicator of whole body metal burdens (Furness et al., 1986). Total PCB concentration in subcutaneous fat (hereafter referred to as fat) was also assessed for individuals from The Nut State Reserve.

2.2. PCB analysis

PCBs were extracted from the tissue using matrix solid-phase dispersion, as outlined in Ling and Huang (1995). Briefly, 0.5 g of sample was ground with C18 material and added to the top of a florisil solid-phase extraction cartridge. The PCBs were eluted using hexane:acetone (9:1). This was concentrated to ~1.5 mL, solvent exchanged to 20 mL hexane, and cleaned by mixing with concentrated trace metal grade sulphuric acid (Merck, Suprapur). The hexane extract was then filtered through sodium sulphate and concentrated to 1 mL after the acid was discarded. The resulting solution was passed through an Agilent PCB solid-phase extraction cartridge as a final clean up step according to the manufacturers' directions. This eluted solution was then concentrated to 1 mL and the internal standard added and transferred to 2 mL vials. The samples were then analysed by a gas chromatograph with electron capture detector (GC-ECD) using a 30 m × 0.25 mm × 0.25 μm AT-5 ms column. Hexachlorobenzene was used as an internal standard, and spikes were performed by spiking samples with 50 μL of undiluted Aroclor 1254 (100 μg/mL) stock standard. Blank results were not detectable, blank spike recovery and sample spike recovery was 92 and 87 per cent, respectively, and the QC standard was 101 per cent.

2.3. Trace element analysis

Muscle samples were freeze-dried for 36 h before shipment for analysis, and then dried in an oven at 30 °C for 48 h to remove residual moisture acquired during transport. Analytical procedures followed those in Bond and Lavers (2011). Feathers were washed repeatedly with deionized water to remove external contaminants. We weighed 15–25 mg of each sample into clean Savillex 15 ml Teflon screw-cap vessels, digested them with 1 mL of 8 M HNO_3, capped them tightly, and placed them on a 70 °C hotplate. An additional 1 mL of HNO_3 was added after 60 min. The hotplate was cooled to 50 °C after 24 h, 1 mL of H_2O_2 added, and the caps removed. Following complete reaction, the vessels were recapped, and placed on a 70 °C hotplate for 3 h. Digested samples were transferred to clean, sealed containers, and diluted 500x using distilled, deionized water. For inductively coupled plasma mass spectrometry (ICP-MS) analysis, 1 mL of the sample solution was pipetted into clean 10 mL tubes, and 4 mL distilled, deionized water added to make a final tube dilution of approximately 2500x.

[1] As the entire bird is often consumed by harvesters, liver and other organ tissues are classified as a meat product under Australian food standards.

Trace element concentrations were measured in a PerkinElmer ELAN DRCII ICP-MS (Friel et al., 1990). Each sample mass was measured for 6 s. Values were corrected for background levels using procedural blanks, and for recovery using values from secondary reference materials within each run. Approximately ten per cent of feather and muscle samples were run in duplicate (Table S4). Secondary reference materials were included for every 15–20 samples. The secondary materials used for feathers were certified human hair samples 6H-09 and 7H-01 from the Centre de Toxicologie du Québec, Institut National de Santé Publique du Québec. Secondary reference materials were certified for concentrations of ^{9}Be, ^{27}Al, ^{51}V, ^{53}Cr, ^{55}Mn, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{75}As, ^{77}Se, ^{98}Mo, ^{107}Ag, ^{111}Cd, ^{118}Sn, ^{121}Sb, ^{137}Ba, ^{201}Hg, ^{205}Tl, ^{208}Pb, and ^{238}U. For muscle, we used mussel standards NIST 2976 and NIST 2977, which are certified for Mg, Al, Cl, Ca, Cr, Fe, Mn, Co, Ni, Cu, Zn, As, Br, Rb, Sr, Cd, Ce, Hg, Pb, and U. We limited our analysis to those elements that could be measured reliably as assessed by the recovery of reference materials and performance of duplicate assays. We therefore excluded Al, Be, Cr, Se, Sn, and U from our feather analysis, and Al, Cl, and Cr from muscle analysis.

Concentrations in feathers are presented in μg/g fresh weight, and those in muscle are presented in μg/g wet weight.

2.4. Statistical analysis

We used a linear regression to examine the relationship between concentrations of elements of toxicological concern (Hg, Pb, As, Cd) in paired feathers and muscle samples using raw and log-transformed values. Relationships were considered significant when $p < 0.05$.

3. Results

3.1. PCB analysis

Total PCB concentrations in fat samples were all below the detection limit (< 0.01 μg/g wet weight).

3.2. Trace element analysis

Recovery of the secondary reference material ranged from 72–117 per cent for feather standards, and 70–122 per cent for muscle standards among all remaining elements for all runs (Tables S1 and S2; Supplemental material). Mean relative S.D. (RSD) among elements ranged from 0.00 to < 0.01 for the single muscle duplicate and from < 0.01 to 4.63 for six duplicate feather samples among all elements.

A summary of Short-tailed Shearwater feather and muscle trace element concentrations is presented in Table S3. Feather concentrations of most elements were highly variable, and coefficients of variation ranged from seventeen per cent (Zn) to 101 per cent (V). Muscle concentrations were also variable, with most elements having a CV < 100 per cent (range: 7–173 per cent).

There were no significant relationships between elemental concentrations in feathers and muscle (all $r^2 < 0.33$, all $p > 0.08$). Relationships between muscle and feather concentrations of toxicologically important elements were poor, and not significant (Cd: linear $r^2 = 0.14$, $p = 0.29$, log $r^2 = 0.16$; Pb: linear $r^2 < 0.001$, $p = 0.96$, log $r^2 < 0.001$; As: linear $r^2 < 0.001$, $p = 0.99$, log r^2 = not converged). We could not examine the relationship between muscle and feather Hg, as 10/14 muscle samples' total Hg concentrations were below the limit of detection.

Muscle comprised 66.99 ± 1.76 per cent moisture. Hg, Cd, and As concentrations in muscle were below food safety standards. In 4/14 samples (29 per cent), Pb concentrations exceeded food safety standards of 0.10 μg/g wet weight, with one individual having 0.49 μg/g, almost 5x the acceptable level (Fig. 2).

Assuming 150 g of breast muscle per Short-tailed Shearwater chick is ingested when they are consumed (Lavers pers. obs.), this represents 0.60 ± 0.26 mg of Cu (range: 0.30–1.00 mg) in breast muscle, which corresponds to 0.008 ± 0.004 mg Cu/kg body mass (range: 0.004–0.014) in a 70 kg human. Five birds had > 0.10 mg Cu/kg body mass. Overall, 8/14 shearwater chicks (57 per cent) exceeded food safety standards for at least one element.

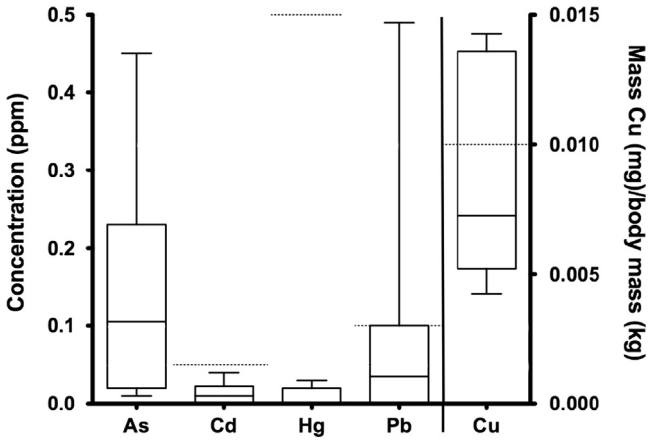

Fig. 2. Concentrations of toxic elements in muscle tissue ($n = 14$) from Tasmanian Short-tailed Shearwaters. Solid lines represent the median value (μg/g) wet weight, boxes represent 25th and 75th percentile, whiskers represent the range. Copper (Cu) presented as mass of Cu in 150 g breast muscle relative to a 70 kg human (right axis). Dotted lines represent the food safety standard (cadmium (Cd): 0.05, mercury (Hg): 0.50, lead (Pb): 0.10 μg/g, Cu: 0.01 mg Cu/kg body mass); food safety standard for As (1.00 μg/g) not presented.

4. Discussion

Lipophilic pollutants, such as PCBs, exhibit a high resistance toward metabolic breakdown; therefore high levels of these compounds can accumulate in apex predators like seabirds, marine mammals, and humans (Braune and Simon, 2003; Dewailly et al., 1992; Yamashita et al., 2007). As a result, seabirds often serve as sentinels of PCB and trace metal contamination in the marine environment (Burger and Gochfeld, 2002, 2004). A previous investigation of homogenised body tissues (including fat) from Short-tailed Shearwater chicks collected in Tasmania in 1983–84 reported PCB concentrations of 0.004–0.027 μg/g (Tanaka et al., 1986). Our results indicated total PCB levels in fat from shearwater chicks sampled at The Nut is < 0.01 μg/g, therefore chicks from Tasmania have remained well below PCB food safety standards (0.2 μg/g; Department of Health and Ageing, 2011) for the past 30 years.

While Short-tailed Shearwater muscle samples were below food safety standards for Hg (0.5 μg/g), Cd (0.05 μg/g), and As (1.00 μg/g), 29 per cent of samples were at or above food safety standards for Pb (0.10 μg/g; all wet weight) (Department of Health and Ageing, 2011). Similar results were reported for Short-tailed Shearwaters taken as bycatch in the North Pacific in 1982 with acceptable concentrations of Hg, but above acceptable standards for Cd (Honda et al., 1990). The amount of Cu measured in Short-tailed Shearwater muscle tissue in 1982 was 0.0008 ± 0.0001 mg per bird, well below levels of concern (Honda et al., 1990). In contrast, Cu concentrations in Tasmanian Short-tailed Shearwater chick muscle sampled in 2011 (0.008 mg/kg) were an order of magnitude greater, and 5/14 samples exceeded the recommended daily intake for humans (0.01 mg Cu/kg) (ATSDR, 2004) and could contribute to health related issues in humans. Birds exceeding food safety standards were found in all areas sampled (Fig. 1).

There are few remaining regulated harvests of seabirds, and only some of these have been examined from a food safety perspective. In New Zealand, Sooty Shearwaters (*Puffinus griseus*, also colloquially called “muttonbirds”) had similar concentrations of Cd and Hg, higher concentrations of As and Cd, and lower concentrations of Pb compared to Short-tailed Shearwaters in our study, but also exhibited significant inter-annual variation in some elements' concentrations (El-Din Bekhit et al., 2011). While El-Din Bekhit et al. (2011) concluded that there was low toxicological risk from consuming Sooty Shearwaters, they assessed their samples

against different food safety standards from New Zealand for As (2 μg/g), Cd (2 μg/g), Pb (0.5 μg/g), and Hg (0.5 μg/g), which are up to five times higher than those used in this study (Department of Health and Ageing, 2011).

Greater Shearwaters (*Puffinus gravis*), and Northern Fulmars (*Fulmarus glacialis*), two other Procellariidae, are harvested, but have not been assessed for contaminants in muscle (Merkel and Barry, 2008; Olsen and Nørrevang, 2005; Richardson, 1984). Other marine birds, such as murres (*Uria* spp.), in the north Atlantic exhibit Cd concentrations that exceed safety standards (ALB, unpublished; Borgå et al., 2006; Nielsen and Dietz, 1989; Wenzel and Gabrielsen, 1995), and eiders (*Somateria* spp.) in the northwest Atlantic have increasing Cd concentrations that are reaching levels of concern for wildlife managers (M.L. Mallory, H.G. Gilchrist and G.J. Robertson, unpublished data).

In many birds, heavy metal and PCB concentrations in feathers and internal tissues are strongly correlated, and non-destructive feather sampling has been advocated as an indicator of total body burden (Jaspers et al., 2011, 2006; Summers et al., 2010). However our analysis found generally poor relationships between elemental concentrations in paired feather and muscle samples, which limits the utility of chick feathers in determining concentrations in internal tissues. Many elements are excreted into growing feathers by birds to eliminate toxic compounds (Braune, 1987; Burger, 1993) and most of the chicks' metal burden is expected to be in feathers rather than blood or muscle (Bond and Diamond, 2009; Kahle and Becker, 1999).

Feather–muscle elemental relationships are seldom measured using breast or body contour feathers (Burger et al., 1993), despite assertions that body feathers best represent overall body metal burdens (Furness et al., 1986; Jaspers et al., 2011). This conclusion is largely derived from correlation analysis (Burger and Gochfeld, 1990; Thompson et al., 1991), which cannot be used to quantify internal contaminant burdens. Some recent studies have used regression analysis to show that Hg in muscle of captive Common Loons (*Gavia immer*) could be predicted reliably from Hg in secondary feathers ($r^2=0.91$) (Kenow et al., 2007), and breast and head feathers from shorebirds and terns in California had varying degrees of utility in predicting muscle Hg (range of $r^2=0.17$–0.71) (range of $r^2=0.17$–0.71; Eagles-Smith et al., 2008). Such quantitative studies are rare, however, and in the case of Short-tailed Shearwaters, no relationship could be found (all $r^2<0.33$). This could be due to variation in chick diet during the period when feathers are grown and the muscle was sampled (Romano et al., 2000). Managers wishing to monitor contaminant levels in harvested Short-tailed Shearwater chicks must therefore sample internal tissues directly, and cannot rely on extrapolating muscle or fat contaminant burdens from concentrations measured in feathers or other tissues.

Harvests of wild species are an important part of human diet and local culture, particularly for remote and indigenous communities (AFN, 2007; Kuhnlein and Chan, 2000). In most cases, traditional food sources are not assessed in relation to food safety standards due to the remote nature of the harvests, and sensitivity surrounding indigenous issues (Stephens et al., 2006), or monitoring occurs sporadically with large gaps between assessments (El-Din Bekhit et al., 2011). Jurisdictional issues may also impede collaboration between government departments responsible for human health and wildlife (Majumdar, 2006). Despite these challenges, concern over the safety of some traditional food sources, such as turtles and marine mammals has led to detailed toxicological assessments which suggest high levels of some toxic metals and organic pollutants in humans are linked to the consumption of these species (Delistraty, 2013; Haswell-Elkins et al., 2006, 2007; Ostertag et al., 2009; Welfinger-Smith et al., 2011).

Toxicological surveys of harvested wild birds are scarce, but of the few published reports, some species exceeded national consumption standards (Braune et al., 1999; Donaldson et al., 1997), while other species may have low toxicological risk (El-Din Bekhit et al., 2011). To our knowledge, there is no regular monitoring and assessment of contaminants in consumed tissues from harvested birds in either the Arctic or Australia/New Zealand, two areas with relatively high rates of seabird consumption in some populations.

In Tasmania, the Department of Primary Industries, Parks, Water, and Environment (DPIPWE) is responsible for the management of the harvest from an ecological perspective—setting bag limits, harvest quotas, and deciding which colonies can be harvested in a given year. The Department of Health and Human Services (DHHS) is responsible for the health and wellbeing of Tasmanians, and these two state government agencies need to work together to ensure that the harvest is both sustainable (DPIPWE), and safe for consumption (DHHS). We would like to see the continuation of a sustainable shearwater harvest that is safe, and which continues to be culturally meaningful for its participants. This requires a collaborative approach among government departments, and with harvesters.

5. Conclusions

Regular monitoring of harmful contaminants in wild foods is urgently required, especially as concentrations of some contaminants are increasing (Streets et al., 2009), and indigenous groups seek to retain or reclaim aspects of their heritage (AFN, 2007). We call for greater integration of human and wildlife health studies, especially concerning wildlife populations that are harvested in remote areas or by indigenous peoples.

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Appendix A. Supplementary information

Supplementary information associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoenv.2013.05.021.

References

AFN, 2007. Traditional Foods: Are They Safe for First Nations Consumption? Assembly of First Nations, Environmental Stewardship Unit, Ottawa.

ATSDR, 2004. Toxicological Profile for Copper. Agency for Toxic Substances and Disease Registry, Public Health Service, U.S. Department of Health and Human Services, Atlanta.

Bond, A.L., Diamond, A.W., 2009. Mercury concentrations in seabird tissues from Machias Seal Island, New Brunswick, Canada. Sci. Total Environ. 407, 4340–4347.

Bond, A.L., Lavers, J.L., 2011. Trace element concentrations in feathers of Flesh-footed Shearwaters (*Puffinus carneipes*) from across their breeding range. Arch. Environ. Contam. Toxicol. 61, 318–326.

Borgå, K., Campbell, L.M., Gabrielsen, G.W., Norstrom, R.J., Muir, D.C.G., Fisk, A.T., 2006. Regional and species specific bioaccumulation of major and trace elements in Arctic seabirds. Environ. Toxicol. Chem. 25, 2927–2936.

Braune, B.M., 1987. Comparison of total mercury levels in relation to diet and molt for nine species of marine birds. Arch. Environ. Contam. Toxicol. 16, 217–224.
Braune, B.M., Malone, B.J., Burgess, N.M., Elliott, J.E., Garrity, N., Hawkings, J., Hines, J., Marshall, H., Marshall, W.K., Rodrigue, J., Wakeford, B., Wayland, M., Weseloh, D.V., Whitehead, P.E., 1999. Chemical Residues in Waterfowl and Gamebirds Harvsted in Canada, 1987–95. Canadian Wildlife Service Technical Report no. 326 1-88.
Braune, B.M., Simon, M., 2003. Dioxins, furans, and non-ortho-PCBs in Canadian Arctic seabirds. Environ. Sci. Technol. 37, 3071–3077.
Burger, J., 1993. Metals in avian feathers: bioindicators of environmental pollution. Rev. Environ. Toxicol. 5, 203–311.
Burger, J., Gochfeld, M., 1990. Tissue levels of lead in experimentally exposed Herring Gull (*Larus argentatus*) chicks. J. Toxicol. Environ. Health Part A 29, 219–233.
Burger, J., Gochfeld, M., 2002. Effects of chemicals and pollution on seabirds. In: Schreiber, J., Burger, J. (Eds.), Biology of Marine Birds. CRC Press, New York, pp. 485–525.
Burger, J., Gochfeld, M., 2004. Marine birds as sentinels of environmental pollution. EcoHealth 1, 263–274.
Burger, J., Rodgers Jr., J.A., Gochfeld, M., 1993. Heavy metal and selenium levels in endangered Wood Storks (*Mycteria americana*) from nesting colonies in Florida and Costa Rica. Arch. Environ. Contam. Toxicol. 24, 417–420.
Callister, D., 1991. Exploitation of the Shot-tailed Shearwater in Tasmania. Traffic Bull. 12, 5–11.
Delistraty, D., 2013. Ecotoxicity and rish to human fish consumers of polychlorinated biphenyls in fish near the Hanford Site (USA). Sci. Total Environ. 445–446, 14–21.
Department of Health and Ageing, 2011. Australia and New Zealand Food Standards Code–Standard 1.4.1–Contaminants and Natural Toxicants. Federal Register of Legislative Instruments F2011C00542. Food Standards Australia New Zealand, Canberra.
Dewailly, É., Laliberté, C., Sauvé, L., Ferron, L., Ryan, J.J., Gingras, S., Ayotte, P., 1992. Sea-bird egg consumption as a major source of PCB exposure for communities living along the Gulf of St Lawrence. Chemosphere 25, 1251–1255.
Donaldson, G.M., Braune, B.M., Gaston, A.J., Noble, D.G., 1997. Organochlorine and heavy metal residues in breast muscle of known-age Thick-Milled Murres (*Uria lomvia*) from the Canadian Arctic. Arch. Environ. Contam. Toxicol. 33, 430–435.
DPIPWE, 2010a. Short-tailed Shearwater (muttonbird) Monitoring Program. Department of Primary Industries, Parks, Wildlife, and Environment, Wildlife Management Branch, Hobart, Australia.
DPIPWE, 2010b. Short-tailed Shearwater Population Monitoring in 2009/10. Department of Primary Industries, Parks, Wildlife, and Environment, Wildlife Management Branch, Hobart, Australia.
Driessen, M.M., Hocking, G.J., 2008. Review of Wildlife Monitoring Priorities. Department of Primary Industries, Parks, Water, and Environment; WIldlife Management Branch, Hobart.
Eagles-Smith, C., Ackerman, J.T., Adelsbach, T.L., Takekawa, J.Y., Miles, A.K., Keister, R.A., 2008. Mercury correlations among six tissues for four waterbird species breeding in San Francisco Bay, California, USA. Environ. Toxicol. Chem. 27, 2136–2153.
El-Din Bekhit, A., Al-Amer, S., Gooneratne, R., Mason, S.L., Osman, K.A., Clucas, L., 2011. Concentrations of trace elementals and organochlorines in mutton bird (*Puffinus griseus*). Ecotoxicol. Environ. Saf. 74, 1742–1746.
Elliott, J.E., 2005. Trace metals, stable isotope ratios, and trophic relations in seabirds from the North Pacific Ocean. Environ. Toxicol. Chem. 24, 3099–3105.
Friel, J.K., Skinner, C.S., Jackson, S.E., Longerich, H.P., 1990. Analysis of biological reference materials, prepared by microwave dissolution, using inductively coupled plasma mass spectrometry. Analyst 115, 269–273.
Furness, R.W., Muirhead, S.J., Woodburn, M., 1986. Using bird feathers to measure mercury in the environment: relationships between mercury content and moult. Mar. Pollut. Bull. 17, 27–30.
Haswell-Elkins, M., Imray, P., Satarug, S., Moore, M.R., O'Dea, K., 2006. Urinary excretion of cadmium among Torres Strait Islanders (Australia) at risk of elevated dietary exposure through traditional foods. J. Expo. Sci. Environ. Epidemiol. 17, 372–377.
Haswell-Elkins, M., McGrath, V., Moore, M., Satarug, S., Walmby, M., Ng, J., 2007. Exploring potential dietary contributions including traditional seafood and other determinants of urinary cadmium levels among indigenous women of a Torres Strait Island (Australia). J. Expo. Sci. Environ. Epidemiol. 17, 298–306.
Hill, A.H., Thompson, C., McCuaig, M.A., 1981. Tasmanian Muttonbird Harvesting and the Future of the Species. Environmental Studies Occasional Paper No. 12. University of Tasmania, 73-146.
Honda, K., Marcovecchio, J.E., Kan, S., Tatsukawa, R., Ogi, H., 1990. Metal concentrations in pelagic seabirds from the North Pacific Ocean. Arch. Environ. Contam. Toxicol. 19, 704–711.
Jaspers, V.L.B., Rodriguez, F.S., Boertmann, D., Sonne, C., Dietz, R., Rasmussen, L.M., Eens, M., Covaci, A., 2011. Body feathers as a potential new biomonitoring tool in raptors: a study on organohaliginated contaminants in different feather rpes and preen oil of west Greenland White-tailed Eagles (*Haliaeetus albicila*). Environ. Int. 37, 1349–1356.
Jaspers, V.L.B., Voorspoels, S., Covaci, A., Eens, M., 2006. Can predatory bird feathers be used as a non-destructive biomonitoring tool of organic pollutants? Biol. Lett. 2, 283–285.
Kahle, S., Becker, P.H., 1999. Bird blood as bioindicator for mercury in the environment. Chemosphere 39, 2451–2457.
Kenow, K.P., Meyer, M.W., Hines, R.K., Karasov, W.H., 2007. Distribution and accumulation of mercury in tissues of captive-reared Common Loon (*Gavia immer*) chicks. Environ. Toxicol. Chem. 26, 1047–1055.
Kuhnlein, H.V., Chan, H.M., 2000. Environment and contaminants in traditional food systems of northern indigenous peoples. Annu. Rev. Nutr. 20, 595–626.
Ling, Y., Huang, I., 1995. Multiresidue-matrix sold-phase dispersion method for determining 16 organochlorine pesticides and polychlorinated biphenyls in fish. Chromatographia 40, 259–266.
Majumdar, D., 2006. Collaboration among government agencies with special reference to New Zealand: a literature review. Soc. Policy J. NZ 27, 183–198.
Merkel, F., Barry, T., 2008. Seabird Harvest in the Arctic. Conservation of Arctic Flora and Fauna (CAFF) International Secretariat, Akureyri, Iceland, CAFF Technical Report No. 16.
Nielsen, C.O., Dietz, R., 1989. Heavy metals in Greenland seabirds. Medd. Grønland Biosci. 29, 1–26.
Nriagu, J.O., 1989. A global assessment of natural sources of atmospheric trace metals. Nature 338, 47–49.
Olsen, B., Nørrevang, A., 2005. Seabird fowling in the Faroe Islands, Traditions of Sea-bird Fowling in the North Atlantic region. The Islands Book Trust, Port of Ness, Scotland, pp. 162–180.
Ostertag, S.K., Tague, B.A., Humphries, M.M., Tittlemeir, S.A., Chan, H.M., 2009. Estimated dietary exposure to fluorinated compounds from traditional foods among Inuit in Nunavut, Canada. Chemosphere 75, 1165–1172.
Richardson, M.E., 1984. Aspects of the ornithology of the Tristan da Cunha group and Gough Island, 1972–1974. Mar. Ornithol. 12, 123–201.
Romano, M.D., Roby, D.D., Piatt, J.F., Kitaysky, A.S., 2000. Effects of Diet on Growth and Development of Nesting Seabirds. Oregon State University, Corvalis, Exxon Valdez oil Spill Restoration Project Final Report (98163N).
Skira, I.J., 1996. Distribution, abundance and conservation status of Short-tailed Shearwaters *Puffins tenuirostris* in Tasmania, Australia. Mar. Ornithol. 24, 1–14.
Skira, I.J., Wapstra, J.E., Towney, G.N., Naarding, J.A., 1985. Conservation of the Short-tailed Shearwater *Puffins tenuirostris* in Tasmania, Australia. Biol. Conserv. 37, 225–236.
Stephens, C., Porter, J., Nettleton, C., Willis, R., 2006. Disappearing, displaced, and undervalued: a call to action for in digenous health worldwide. Lancet 367, 2019–2028.
Streets, D.G., Zhang, Q., Wu, Y., 2009. Projection of global mercury emissions in 2050. Environ. Sci. Technol. 43, 2983–2988.
Summers, J., Gaines, K., Garvin, N., Stephens, W., Cumbee, J., Mills, G., 2010. Feathers as bioindicators of PCB exposure in Clapper Rails. Ecotoxicology 19, 1003–1011.
Sweet, L.I., Zelikoff, J.T., 2001. Toxicology and immunotoxicology of mercury: a comparative review in fish and humans. J. Toxicol. Environ. Health Part B. Crit. Rev. 4, 161–205.
Tanaka, H., Ogi, H., Tanabe, S., Tatsukawa, R., Oka, N., 1986. Bioaccumulation and metabolism of PCBs and DDE in Short-tailed Shearwater *Puffinus tenuirostris* during its transequatorial migration and in the wintering and breeding grounds. Mem. Nat. Inst. Polar Res. 40, 434–442.
Thompson, D.R., Hamer, K.C., Furness, R.W., 1991. Mercury accumulation in Great Skuas *Catharacta skua* of known age and sex, and its effects upon breeding and survival. J. Appl. Ecol. 28, 672–684.
Vertigan, K., 2010. The Life-history of Short-tailed Shearwaters (*Puffinus tenuirostris*) in Response to Spatio-temporal Environmetnal Variation (B.Sc. (Honours) thesis). University of Tasmania, Hobart.
Vlietstra, L.S., Coyle, K.O., Kachel, N.B., Hunt Jr., G.L., 2005. Tidal fronts affect the size of prey used by a top marine predator, the Short-tailed Shearwater (*Puffinus tenuirostris*). Fish. Oceanogr. 14, 196–211.
Welfinger-Smith, G., Minholtz, J.L., Byrne, S., Waghiyi, V., Gologergen, J., Kava, J., Apatiki, M., Ungott, E., Miller, P.K., Arnason, J.G., Carpenter, D.I., 2011. Organochlorine and metal contminants in traditional foods from St. Lawrence Island, Alaska. J. Toxicol. Environ. Health Part A 74, 1195–1214.
Wenzel, C., Gabrielsen, G.W., 1995. Trace element accumulation in three seabird species from Hornøya, Norway. Arch. Environ. Contam. Toxicol. 29, 198–206.
Woehler, E.J., Raymond, B., Watts, D.J., 2006. Convergence or divergence: where do Short-tailed Shearwaters forage in the Southern Ocean? Mar. Ecol. Prog. Ser. 324, 261–270.
Wolfe, M.F., Schwartzbach, S., Sulaiman, R.A., 2009. Effects of mercury on wildlife: a comprehensive review. Environ. Toxicol. Chem. 17, 146–160.
Yamashita, R., Takada, H., Murakami, M., Fukuwaka, M., Watanuki, Y., 2007. Evaluation of noninvasive approach for monitoring PCB pollution in seabirds using preen gland oil. Environ. Sci. Technol. 41, 4901–4906.

SUPPLEMENTAL MATERIAL

Table S1. Recovery of certified reference materials (CRM) used to determine concentrations in shearwater feathers (n = 10). # > LoD = number of samples above the minimum level of detection (n = 2 replicates of the reference materials).

Element	# > LoD	CRM concentration (mg/kg)	% recovery
Al	0	159	93%
Mn	1	5.64	109%
Co	2	0.476	98%
Ni	1	6.6	103%
Cu	0	132	101%
Zn	0	179	98%
As	12	2.64	89%
Mo	1	0.473	102%
Ag	7	0.77	104%
Cd	3	0.24	117%
Sb	39	0.205	104%
Ba	2	1.48	98%
Hg	5	4.49	96%
Tl	0	0.18	106%
Pb	0	5.28	101%

Table S2. Recovery of certified reference materials (CRM) used to determine concentrations in shearwater muscle (n = 14). # > LoD = number of samples above the minimum level of detection (n = 4 replicates of the reference materials).

Element	# > LoD	CRM concentration (mg/kg)	% recovery
Mg	0	5300	90%
V	14	–	–
Mn	0	33	108%
Co	7	0.48	80%
Cu	0	9.42	92%
Zn	0	335	93%
As	0	33.3	92%
Br	3	235	86%
Sr	1	69.3	88%
Ag	10	0.033	88%
Cd	6	0.82	97%
Hg	10	0.63	120%
Pb	4	2.27	95%

Table S3. Trace element concentrations in feather (n = 10) and muscle tissue (n = 14) from Tasmanian Short-tailed Shearwaters. Values are presented as mean ± SD in μg/g fresh weight for feathers, μg/g wet weight for muscle. <LoD: all samples below limit of detection. Minimum and maximum values provided in parentheses. When the minimum was <LoD, mean ± S.D. is for those samples with measurable concentrations.

Element/ Compound	Feathers	Muscle
Mg	-	326.54 ± 21.40 (262.71-357.68)
Al	607.57 ± 538.13 (109.45-1927.56)	-
V	0.64 ± 0.64 (0.13-2.31)	<LoD (0.18)
Fe	-	129.23 ± 38.69 (77.33-188.03)
Mn	4.82 ± 3.44 (1.94-12.77)	0.53 ± 0.14 (0.27-0.76)
Co	0.09 ± 0.08 (0.00-0.29)	0.01 ± 0.01 (<LoD-0.02)
Ni	4.28 ± 7.08 (0.57-23.19)	-
Cu	18.51 ± 3.69 (11.17-23.88)	4.00 ± 1.71 (1.97-6.66)
Zn	90.09 ± 15.56 (65.97-115.23)	14.25 ± 6.11 (8.46-28.72)
As	0.26 ± 0.28 (0.00-0.86)	0.15 ± 0.14 (0.01-0.45)
Br	-	1.27 ± 0.91 (<LoD-2.98)
Rb	-	1.39 ± 0.25 (1.11-1.80)
Sr	-	0.13 ± 0.11 (<LoD-0.46)

Mo	0.30 ± 0.12 (0.14-0.56)	-
Ag	0.09 ± 0.06 (0.00-0.21)	0.39 ± 0.20 (<LoD-0.62)
Cd	0.03 ± 0.02 (0.01-0.09)	0.01 ± 0.01 (<LoD-0.04)
Sb	<LoD (0.02)	<LoD (0.03)
Ba	1.74 ± 097 (0.88-3.46)	-
Ce	-	0.02 ± 0.02 (<LoD-0.08)
Hg	0.14 ± 0.08 (0.05-0.28)	0.03 ± 0.00 (<LoD-0.03)
Tl	0.00 ± 0.00 (0.00-0.01)	<LoD (0.02)
Pb	0.37 ± 0.17 (0.19-0.70)	0.07 ± 0.13 (<LoD-0.49)

Table S4. Summary of duplicate Short-tailed Shearwater muscle samples. Data are in µg/g. % Difference = (analysis 1 – analysis 2) / mean of both analyses; n = 2 duplicates (14% of total samples). Samples where concentrations were below the level of detection are not included.

	Sample 1			Sample 2		
Element	Analysis 1	Analysis 2	% Difference	Analysis 1	Analysis 2	% Difference
Mg	330	335	1.4	1532	1430	6.9
Mn	0.76	0.59	25.5	2.91	2.74	15.8
Co	< LoD	< LoD	-	< LoD	0.04	-
Cu	6.34	6.33	0.2	26.08	23.85	8.9
Zn	22.99	17.88	25.0	55.16	50.74	8.3
As	0.02	0.01	40.7	0.58	0.62	6.7
Br	1.19	1.51	23.2	34.0	24.7	31.7
Sr	0.16	0.21	26.8	0.97	0.35	93.5
Ag	0.13	0.62	129.8	0.08	< LoD	-
Cd	0.01	0.01	0.0	< LoD	< LoD	-
Hg	0.03	0.02	14.6	< LoD	< LoD	-
Pb	< LoD	0.07	-	0.01	< LoD	-