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RESEARCH ARTICLE

Trace element concentrations in feathers of seven petrels (*Pterodroma* spp.)

Susan M. Philpot[1] · Jennifer L. Lavers[1] · Dayanthi Nugegoda[2] · Morgan E. Gilmour[3] · Ian Hutton[4] · Alexander L. Bond[1,5,6]

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Abstract

Gadfly petrels (*Pterodroma* spp.) are one of the most threatened and poorly studied seabird groups, and as marine predators, are exposed to biomagnified and bioaccumulated chemical pollutants from their prey. We quantified trace element concentrations in breast feathers of seven petrel species that breed in the southern hemisphere to quantify current concentrations. Selenium (Se) concentrations were significantly lower in chicks than adults; this was not observed for zinc (Zn) or lead (Pb). Overall, the species examined here exhibited similar concentrations of Se, with Pb and Zn concentrations more variable among species. The mean Se concentration in adult birds exceeded those thought to be potentially deleterious, and three species had concentrations that were above the assumed threshold for Pb toxicity. Further investigation of potentially toxic trace elements in gadfly petrels is warranted.

Keywords Feathers · Lead · Petrels · Procellariiformes · Selenium · Zinc

Introduction

Exposure of marine and coastal environments to metal and metalloid trace elements has risen since the industrial revolution, with their increased use in agricultural, industrial, domestic and technological applications (Ayres 1992; Clark 2001). This has led to particular concerns about food safety, and ecosystem health and fitness (Richir 2016). Trace element distributions are not uniform in the marine environment, differing vertically within the water column, and regionally across the globe (Boye et al. 2012). On the continental margin, several anthropogenic sources contribute to contamination levels. Point source inputs from industry, agriculture and river run-off can contaminate coastal biota heavily, particularly in areas adjacent to industrialisation (Boye et al. 2012; Finger et al. 2015). Natural input from upwelling along the continental shelf re-suspends elements from sediments and vertically mixes enriched deep water (Rejomon et al. 2010). Conversely, the open ocean is generally not rich in trace elements as the geochemical and biological processes that influence concentrations tend to operate over a broader scale (Rainbow 1985).

Assessing the health of complex ecosystems can often be achieved using a bio-indicator (Furness and Camphuysen 1997; Markowski et al. 2013). Monitoring living organisms provides data on pollutants' abilities to bioaccumulate and biomagnify, and the opportunity to observe possible behavioural and physical symptoms of toxicity (Markowski et al. 2013). As marine predators, seabirds reflect contamination through the marine food web, making them ideal sentinels for monitoring ecosystem change (Burger 1993; Burger and Gochfeld 2004). Furthermore, they are philopatric, colonial

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✉ Jennifer L. Lavers
Jennifer.Lavers@utas.edu.au

1 Institute for Marine and Antarctic Studies, University of Tasmania, 20 Castray Esplanade, Battery Point, Hobart, Tasmania 7004, Australia

2 School of Science, RMIT University, GPO Box 71, Bundoora, Victoria, Australia

3 Ocean Sciences Department, University of California, Santa Cruz, CA 95060, USA

4 Lord Howe Island Museum, P.O. Box 157, Lord Howe Island, New South Wales 2898, Australia

5 RSPB Centre for Conservation Science, Royal Society for the Protection of Birds, The Lodge, Sandy, Bedfordshire SG19 2DL, UK

6 Present address: Bird Group, Department of Life Sciences, The Natural History Museum, Akeman Street, Tring, Hertfordshire HP23 6AP, UK

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breeders, allowing spatial and temporal data to be collected efficiently (Furness and Camphuysen 1997). Seabirds' ability to reflect environmental pollutants within their tissues has been highlighted by several studies (e.g. Finger et al. 2016; Markowski et al. 2013). The concentration of some trace elements in feathers reflect blood concentrations during the 3- to 4-week feather forming process, making feathers a permanent record of consumption in that period (Burger and Gochfeld 1997). Consequently, feathers formed while at the breeding colony may reflect contamination in the local environment. However, not all trace elements acquired are eliminated during moult and some, like mercury (Hg), can accumulate in internal organs before being redistributed to growing feathers. There is a strong relationship between Hg in body tissue and feather content (Braune and Gaskin 1987; Monteiro and Furness 2001).

The gadfly petrels (*Pterodroma* spp.) are one of the most threatened and poorly studied seabird groups (Brooke et al. 2010; Croxall et al. 2012). The primary threat to many petrel populations is predation from introduced species, particularly on nest-bound chicks (e.g. Caravaggi et al. 2018; Cuthbert et al. 2013). The effects of invasive species and bycatch have been well studied, and there are many successful programmes in place to monitor and mitigate these threats (Anderson et al. 2011; Jones et al. 2016). In contrast, trace element contamination has only recently been identified as a threat to some *Pterodroma* petrels (Becker et al. 2016; Lavers and Bond 2016). For instance, on Gough Island, Hg concentrations in the feathers of Atlantic petrels *Pterodroma incerta* increased by 49% over 24 years to concentrations that could be detrimental, exceeding 20,000 ng/g (Becker et al. 2016). However, for the majority of species, no data exist, making a rigorous risk assessment impossible. Here, we quantify trace element concentrations in breast feathers of seven *Pterodroma* petrel species from four locations spanning the southern hemisphere: Henderson Island, Gough Island, Lord Howe Island and Breaksea Island (Table 1, Fig. 1) to identify whether current concentrations are likely to pose a toxicological risk to the health of the species.

Materials and methods

Sample collection

Samples were collected at four different locations (Fig. 1). Breast feathers were collected from a combination of breeding adult and fledgling Henderson *P. atrata* and Kermadec petrels *P. neglecta*, and adult Murphy's petrel *P. ultima* on Henderson Island, Pitcairn Island Group (24.3744° S, 128.3271° W); from breeding adult Atlantic petrels on Gough Island, Tristan da Cunha (40.3186° S, 9.9353° W); adult Black-winged *P. nigripennis* and providence petrels *P. solandri* on Lord Howe Island, Australia (31.5553° S, 159.0821° E) and adult Great-winged petrels *P. macroptera* on Breaksea Island, Australia (35.0632° S, 118.0530° E; Table 1). Breast feathers were sampled as they are the most accurate indicator of whole-body metal burden (Furness et al. 1986). All samples were collected under the appropriate permits and stored dry in sterile bags or envelopes at room temperature.

Analytical methods

To remove external contamination, feathers were washed in a 2:1 solution of chloroform/methanol (Lavers et al. 2014; Paritte and Kelly 2009). Feathers were submerged in solution and placed on an orbital shaker for 12 h, before being removed, rinsed in Milli-Q® water and air dried. Approximately 10–15 mg (fresh weight) of feather (a homogenised sub-sample of 4–6 feathers per bird) was weighed and placed in acid washed glass test tubes. The use of multiple feathers per sample is recommended due to variation in metal concentrations which occurs among individual feathers (Bond and Diamond 2008).

The feathers were digested in 1 ml nitric acid (HNO_3, 70%) on a heating block at 70 °C for 24 h, with 3 drops of hydrogen peroxide (H_2O_2, 30%) added to enhance and achieve digestion. During this process, the test tubes were capped to prevent evaporation and potential sublimation. Samples were increased to 10 ml using Milli-Q water and filtered through a

Table 1 Number of adult and fledgling *Pterodroma* spp. sampled for this study (*n*), ICUN Red List status and population trend (BirdLife International 2017)

Common name	Scientific name	Status	Population trend	Sampling location	Adult (*n*)	Fledgling (*n*)	Date collected
Henderson petrel	*P. atrata*	Endangered	Stable	Henderson Is.	21	4	Jul–Aug 2015
Kermadec petrel	*P. neglecta*	Least concern	Decreasing	Henderson Is.	7	3	Jul–Aug 2016
Murphy's petrel	*P. ultima*	Near threatened	Decreasing	Henderson Is.	22	0	May–Aug 2015
Atlantic petrel	*P. incerta*	Endangered	Decreasing	Gough Is.	15	0	Jul–Sep 2016
Black-winged petrel	*P. nigripennis*	Least concern	Decreasing	Lord Howe Is.	17	0	Jan 2017
Providence petrel	*P. solandri*	Vulnerable	Increasing	Lord Howe Is.	16	0	Oct 2016
Great-winged petrels	*P. macroptera*	Least concern	Decreasing	Breaksea Is.	16	0	Jul 2015

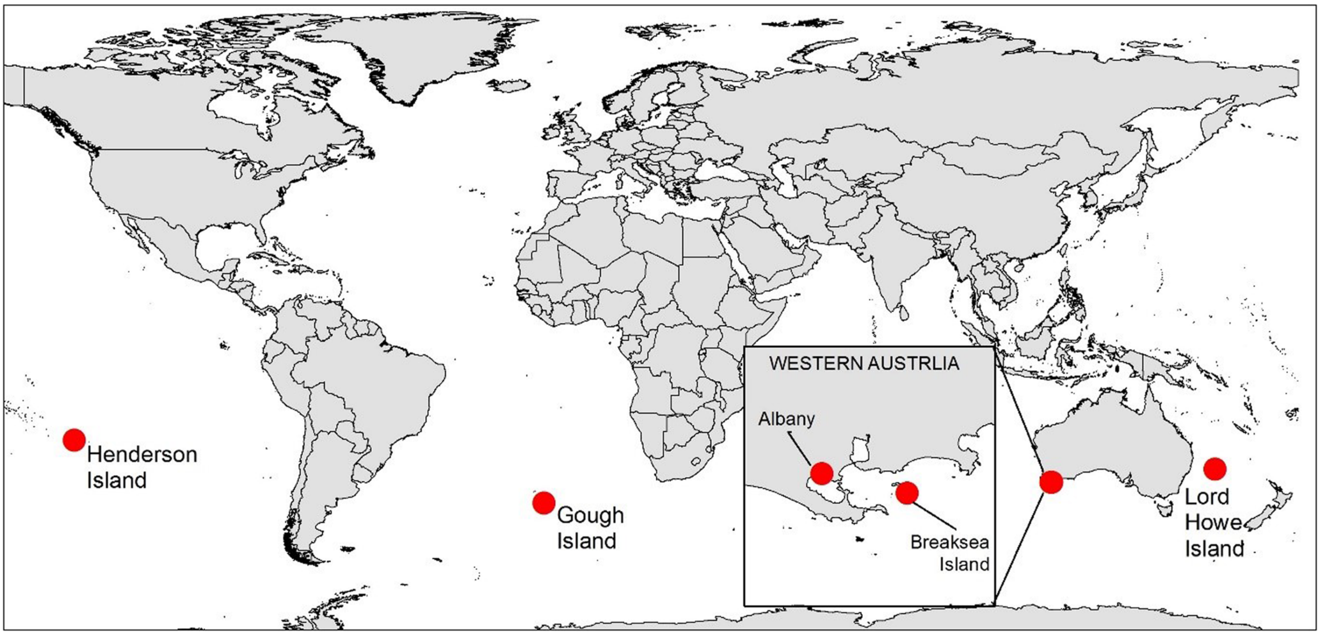

Fig. 1 *Pterodroma* spp. breast feather collection sites

0.45-μm disposable filter. Inductively coupled plasma mass spectrometry was used to analyse the trace elements (i.e. As, Cd, Cu, Hg, Pb, Se and Zn) at the Australia Centre for Research on Separation Science, RMIT University, Melbourne (Finger et al. 2015). Prior to analysis, 2 mL of the digested feather solution was diluted with 8 mL of Milli-Q water. Analytical duplicates were performed for all feather samples.

To validate analytical methods and assure reliable results, a reference material (human hair, ERM-DB001) certified for concentrations of As, Cd, Cu, Hg, Pb, Se and Zn was analysed for every 15 to 20 samples (Table 2).

Data analysis

The final dataset only included those elements which were analysed reliably, meaning a recovery in the range of 70–130% (Finger et al. 2016). This restricted analysis to Zn, Se and Pb (Table 2). Samples with a concentration below the detection limit of the ICP-MS were excluded, and the remaining analytical duplicates averaged. Hg concentration in the reference material was very low; hence, reliable recovery could not be estimated based on analysis of sample weights used for feather analysis. Final results are reported as nanogramme/gramme (parts per billion; ppb) and expressed as mean ± standard deviation (range). Data were not normally distributed, and log-transforming data did not improve normality, so we then used a Kruskal-Wallis test followed by a Dunn's test (with a Benjamini-Yekutieli correction) for pairwise comparisons using R 3.3.3 (R Core Team 2018) to test if concentrations of Zn, Se and Pb differed among species; fledgling samples were excluded from this analysis. A Welch's *t* test was used to test for differences in concentrations (Se, Zn, Pb) between age classes for Henderson and Kermadec petrels. Results were considered significant when $p < 0.05$.

Results

Differences among species

There were no differences in Se concentrations among species; however, some species differed in their concentrations of Pb and Zn (Table 3). For example, Atlantic petrels exhibited

Table 2 Recovery, mean, standard deviation (SD) and CV of certified reference material (human hair; Zn, Se, Pb ng/g) that were analysed reliably ($n = 5$)

	Zn	Se	Pb	As	Cu	Cd	Hg
Certified	209,000	3240	2140	44	33,000	125	365
Mean	190,953	3501	2730	<LOD	50,029	640	1
SD	7816	999	145	<LOD	3907	539	856
CV	0.04	0.29	0.05	<LOD	0.08	0.84	867.17
% recovery	91.00	108.00	128.00	<LOD	152.00	512.00	0.27

Table 3 List of significant comparisons (Pb and Zn) across adult *Pterodroma* spp.: sample location, Z statistic and adjusted *p* value

Species comparison	Location	Z statistic	*p* value
Lead (Pb)			
Atlantic - Providence	Gough Is. - Lord Howe Is.	− 2.347	0.009
Kermadec - Atlantic	Henderson Is. - Gough Is.	2.328	0.010
Henderson - Atlantic	Henderson Is. - Gough Is.	2.175	0.015
Great-winged - Atlantic	Breaksea Is. - Gough Is.	2.172	0.015
Atlantic - Black-winged	Gough Is. - Lord Howe Is.	− 1.962	0.025
Murphy's - Providence	Henderson Is. - Lord Howe Is.	− 1.731	0.042
Murphy's - Kermadec	Henderson Is. - Henderson Is.	− 1.704	0.044
Zinc (Zn)			
Great-winged - Providence	Breaksea Is. - Lord Howe Is.	2.596	0.005
Great-winged - Murphy's	Breaksea Is. - Henderson Is.	2.302	0.011
Great-winged - Kermadec	Breaksea Is. - Henderson Is.	2.133	0.016
Providence - Black-winged	Lord Howe Is. - Lord Howe Is.	− 1.802	0.036

There were no significant differences in Se concentrations among species

significantly lower Pb concentrations than Henderson (Z = 2.17, $p < 0.01$) and Great-winged petrels ($Z = 2.17$, $p < 0.01$) while Great-winged petrels had significantly higher concentrations of Zn than providence petrels ($Z = 2.59$, $p < 0.01$). Only a minority of comparisons among species were statistically significant (Table 3).

The individual with the highest Pb concentration was an adult Henderson petrel (62,950 ng/g), followed by an adult Great-winged petrel (37,227 ng/g). Overall, Great-winged petrels had the greatest proportion of individuals (37.5%) exceeding the lowest observed adverse effect level (LOAEL) for Pb (4000 ng/g; Burger 1993), with Murphy's (28.6%) and Henderson petrels (23.8%) also a cause for concern.

All of the Henderson, Great-winged, Murphy's and providence petrels sampled exceeded the provisional LOAEL for Se in feathers (5000 ng/g; Ohlendorf and Heinz 2011), as did a large proportion of Atlantic (93.3%), Black-winged (88.2%) and Kermadec (85.7%) petrels. This LOAEL does not necessarily imply toxicity, as seabirds may naturally have higher background concentrations (Ohlendorf and Heinz 2011). However, all groups have several individuals that exceed 10,000 ng/g (twice the LOAEL).

Differences between age classes

Mean Se concentrations were significantly higher in adult Henderson ($t = 3.93$, df = 22.98, $p < 0.01$) and Kermadec petrels ($t = 3.86$, df = 7.32, $p < 0.01$), than fledglings of these species. However, there were no differences in Zn or Pb concentrations between fledgling and adult Henderson (Zn: $t = -0.08$, df = 6.17, $p = 0.94$; Pb: $t = 1.54$, df = 21.18, $p = 0.14$) or Kermadec petrels (Zn: $t = -0.35$, df = 3.17, $p = 0.75$; Pb: $t = -0.87$, df = 2.02, $p = 0.47$).

Discussion

Procellariiformes display wide-ranging foraging behaviour, travelling great distances during the breeding period (Phillips et al. 2007). Trace element concentrations in feathers grown on the breeding grounds would be expected to represent contamination in the local environment (Carravieri et al. 2014; Onley and Scofield 2007). However, accumulation of some trace elements since the last moult (e.g. Hg and Pb) can be shunted into the forming feather to rid the body of excess concentrations. Therefore, knowledge of a species life history enhances the ability to interpret trace element data from feathers (Burger 1993; Furness and Camphuysen 1997). Trace element concentrations among species from the same location may vary depending on each species feeding habits, migration patterns and biological requirements (Borgå et al. 2006; Wenzel and Gabrielsen 1995). Individuals' foraging habitat and species' functional feeding groups influence the concentrations of trace elements accumulated (Anderson et al. 2010). For elements that biomagnify (e.g. Se, Hg), higher trophic level organisms, including seabirds, generally have higher concentrations (Chapman et al. 2010).

Zinc (Zn)

Zinc is an essential trace element, and is required for feather formation (Sunde 1972). Zn concentrations in feathers vary widely among bird species (Honda et al. 1990), and there is currently no LOAEL in feather tissue for seabirds. In a study by Bocher et al. (2003), Zn concentrations in seabird tissues (muscle, kidney, and liver) did not reflect dietary intake, suggesting that the nutritional requirement of this essential element may regulate absorption. Alternatively, variability could be related to molecular interactions (i.e. the affinity of Zn to bind with other metals; Bocher et al. 2003). Black-winged and providence petrels from Lord Howe Island exhibited significantly different concentrations of Zn, as well as substantially higher Zn concentrations than sympatrically breeding flesh-footed shearwater *Ardenna carneipes* (Zn: 8588 ng/g; Bond and Lavers 2011). Overall, the mean Zn concentrations for the species examined in this study were similar to the upper end of ranges reported in other petrel species (Anderson et al. 2010; Cipro et al. 2014), but the highest reported for *Pterodroma* species (Table 4). While there are no reported seabird cases of Zn toxicity in the literature, high concentrations of Zn (2000 ppm) in mallard ducks *Anas platyrhynchos* reduced gonad size to a degree where reproductive function may be diminished or lost (Gasaway and Buss 1972).

Lead (Pb)

Pb is a non-essential element that plays no biological role in the function of the marine ecosystem (Elliott et al. 1992). Feather Pb concentrations are often reflective of concentrations in internal tissues, making them a good indicator of whole-body burden (Burger 1993). A LOAEL of 4000 ng/g of Pb in feathers is commonly used as a guideline to indicate sub-lethal effects in seabirds (Burger 1993; Burger and Gochfeld 2000b). The effects of Pb toxicity include stunted chick growth, behavioural abnormalities and interrupted breeding (Burger 1993). In this study, mean Pb concentrations in four groups exceeded the presumed LOAEL: fledgling Kermadec petrels and adult Murphy's, Henderson and Great-winged petrels. A few individuals exhibited extremely high Pb concentrations, well above the reported mean concentrations (Table 4). Pb contamination in these groups may be affecting population health and reproductive fitness, although currently there is no evidence of this. Predation is a major contributing factor to the decline of *Pterodroma* species (Brooke et al. 2010; Cuthbert et al. 2013), and could possibly be masking any effect of high Pb concentrations (or other contaminants).

Great-winged petrels exhibited the highest concentrations of Pb, with Breaksea Island being the only inshore location sampled in this study. Breeding seabird populations that forage in proximity to industrialised sites and human settlements, such as locations near the city of Albany, Western Australia (Fig. 1), are likely at risk of trace element contamination. In Victoria, Australia, trace element concentrations in Little Penguins *Eudyptula minor*, including Pb, were linked to the level of industrialisation adjacent to the population's foraging zone (Finger et al. 2015). Since European colonisation, Australia's coal and ore resources have been mined extensively. This has led to an increase in atmospheric, marine and coastal pollution (Marx et al. 2010; Mudd 2007). Pb concentrations off the coast of Albany have increased in the past 50 years (Serrano et al. 2016). Pb contamination has also been an environmental and health issue for the human population nearby in Esperance, Western Australia (Gulson et al. 2009, 2012). Since the establishment of industry, a major point source of Pb pollution came from a chemical plant producing sulphuric acid (H_2SO_4) which emitted effluents into Princess Royal Harbour, just west of Breaksea Island (Talbot 1983). However, contamination may be attributed to a number of sources including dredging projects, vessel traffic, oil pollution, as well as mining and agricultural activities (Australian Government 2012).

Selenium (Se)

Se is a metalloid element that birds require in small amounts for good health (e.g. immune function), but is toxic in excessive concentrations (Franson et al. 2007; Ohlendorf and Heinz 2011). Symptoms of Se toxicity in aquatic birds include reproductive impairment and poor body condition; however, reproductive failure is possible with no observable effects on the adult bird (Lemly 1996; Ohlendorf et al. 1986; Ohlendorf and Heinz 2011). In general, Se transfers through food webs, biomagnifying from the base through to high-trophic consumers (Chapman et al. 2010). However, Anderson et al. (2010) found a weak relationship between Se and trophic position and foraging location among Procellariiformes. Feather Se may be reflective of a bird's historical exposure, but distribution and depuration of Se in feathers is variable, a consequence of metabolic function (Burger 1993; Goede 1991), and a possible explanation for concentrations not differing among species of this study. Using feathers as an indicator of Se body burden is therefore more problematic than other trace elements, but can be useful when exposure history and external contamination are accounted for (Burger 1993). External contamination by preen oil and sediments was mitigated in this study by adopting strict washing procedures (Paritte and Kelly 2009; Surmacki and Nowakowski 2007). For Se, 5000 ng/g in breast feathers has been identified as a provisional LOAEL (Ohlendorf and Heinz 2011; USDI 1998). However, marine birds may have naturally higher concentrations of trace elements in their tissues (Ohlendorf and Heinz 2011).

The mean Se concentrations in adults for all species were above this provisional threshold, although fledgling Kermadec petrels were well below the LOAEL (Table 4). Henderson, Murphy's, Great-winged, Kermadec and providence petrels appeared to exhibit some of the highest Se feather concentrations reported for petrel species (Anderson et al. 2010; Carvalho et al. 2013; Gochfeld et al. 1999); but are within a similar range to the southern giant petrel *Macronectes giganteus* (Se: 9757 ng/g) sampled in the southern Atlantic Ocean (Anderson et al. 2010). Trace elements accumulate in the internal tissue of birds, which are then mobilised into the blood stream to be excreted. There is currently no reference which states what percentage of Se female

Table 4 Review of feather trace element (Zn, Se, Pb) concentrations (mean ± standard deviation (range)) reported for *Pterodroma* spp., by increasing mean concentration, including results of this study, and current hypothesised lowest observable adverse effects levels (LOAEL)

Petrel species	Number	Age class	Zn (ng/g)	Source
Hypothesised LOAEL			Not available	
Bonin	8	Fledgling	26,880 ± 10,060	Lavers and Bond (2016)
Grey-faced	220	Adult	65,430 ± 10,710	Lyver et al. (2017)
Black-winged	17	Adult	96,537 ± 27,342 (62,580–143,335)	This study
Atlantic	15	Adult	103,902 ± 39,592 (56,863–174,618)	This study
Providence	16	Adult	105,086 ± 31,154 (63,597–183,733)	This study
Kermadec	7	Adult	145,625 ± 61,271 (84,198–259,337)	This study
Great-winged	16	Adult	158,631 ± 99,384 (71,859–385,770)	This study
Kermadec	3	Fledgling	162,850 ± 76,469 (115,985–251,093)	This study
Murphy's	22	Adult	206,630 ± 175,906 (114,662–983,175)	This study
Henderson	21	Adult	229,201 ± 112,923 (115,411–528,895)	This study
Henderson	4	Fledgling	232,503 ± 73,002 (147,233–325,249)	This study
			Se (ng/g)	
Hypothesised LOAEL			5000 ng/g	Ohlendorf and Heinz (2011)
Kermadec	3	Fledgling	1914 ± 1246 (540–2973)	This study
Bonin	20	Fledgling	4860 ± NA	Gochfeld et al. (1999)
Henderson	4	Fledgling	5810 ± 2411 (2312–7838)	This study
Bonin	27	Adult	7850 ± NA	Burger and Gochfeld (2000a)
Black-winged	17	Adult	8752 ± 3043 (3729–14,581)	This study
Atlantic	15	Adult	9234 ± 4587 (4351–23,288)	This study
Kermadec	7	Adult	9994 ± 5197 (0–16,350)	This study
Providence	16	Adult	10,799 ± 3819 (6528–23,070)	This study
Murphy's	22	Adult	14,051 ± 3925 (8919–23,984)	This study
Great-winged	16	Adult	14,393 ± 18,712 (5161–83,874)	This study
Henderson	21	Adult	19,451 ± 14,914 (8175–81,874)	This study
			Pb (ng/g)	
Hypothesised LOAEL			4000 ng/g	Burger (1993)
Grey-faced	220	Adult	50 ± 140	Lyver et al. (2017)
Bonin	8	Fledgling	1190 ± 920	Lavers and Bond (2016)
Kermadec	7	Adult	1668 ± 454 (1048–2023)	This study
Henderson	4	Fledgling	1678 ± 1045 (373–2668)	This study
Black-winged	17	Adult	2156 ± 1125 (770–4181)	This study
Atlantic	15	Adult	2474 ± 4358 (427–17,975)	This study
Providence	16	Adult	2974 ± 5080 (384–20,079)	This study
Kermadec	3	Fledgling	4091 ± 4796 (1272–9630)	This study
Murphy's	22	Adult	4437 ± 5959 (827–28,864)	This study
Henderson	21	Adult	6220 ± 13,260 (880–62,950)	This study
Great-winged	16	Adult	6481 ± 9022 (1185–37,227)	This study

petrels sequester into feathers. However, Ackerman et al. (2016) indicate Se concentrations in eggs are positively correlated with Se in the liver of the female parent. Whereas adults have longer periods to assimilate and mobilise metals, chicks tend to have a much shorter period over which to accumulate contaminants (Burger 1993). In this study, this pattern was evident in the Se results, but not Pb and Zn. Adult Henderson and Kermadec petrels exhibited a substantially higher mean concentration of Se than fledglings; similar results have been reported in other seabird species (Burger and Gochfeld 1995; Gochfeld et al. 1999; Wenzel and Gabrielsen 1995). Se is primarily sequestered into the developing egg from the reproducing female (Ohlendorf and Heinz 2011). At hatching, the concentration of trace elements in chicks is therefore reflective of the female parent. Exposure to elements beyond this point (i.e. as the chick develops and grows feathers) reflects prey items provided by the parents (Burger and Gochfeld 2000a). The higher Se concentration in adult birds could suggest mobilisation of Se from internal organs that has been accumulated over time (Burger et al. 1994). It may also suggest that adult birds are consuming or absorbing more Se than what they are regurgitating to their young. To maximise energy and foraging efficiency, breeding pelagic seabirds (e.g. petrel species) predominantly allocate energy from short foraging trips towards chicks, and self-feed on longer trips. These provisioning parameters mean the adult bird is likely consuming a different diet than what is being fed to the chick (Cherel et al. 2002; Weimerskirch et al. 2003).

Conclusions

The majority of *Pterodroma* petrels are poorly studied, and many are of conservation concern. Predation by introduced species has been one of the main recognised threats in the past; however, anthropogenic pollution is an increasing concern for many marine species (Afshan et al. 2014; Lavers et al. 2014; Lehnert et al. 2016). The results of this study provide insight into chemical pollutant levels that may be contributing to the decline of some petrel species, by identifying populations that are exceeding the LOAEL for Pb and possibly Se. This implies that some species may be affected negatively by elevated concentrations of these elements, or that we require a better understanding of the toxicological consequences of potentially hazardous trace element concentrations in gadfly petrels. The diet and foraging behaviour of *Pterodroma* species are poorly understood compared with other Procellariiformes (e.g. albatrosses); however, they are known to eat myctophids and squid, which often have high concentrations of elements such as Zn, Hg and Cd (Bester et al. 2010, Penicaud et al. 2017). In response, it is possible some *Pterodroma* may have developed a higher toxicity threshold, which has been reported for Hg in some seabird species (Bustamante et al. 2016). More research on the functional feeding groups and diet provisioning of these species will help determine pathways of contamination and the trophic level at which the species are exposed to trace elements (Ruelas-Inzunza and Páez-Osuna 2008; Signa et al. 2013).

Regardless of their conservation status, the majority of the petrel species examined here exhibit declining population trends (Table 1). Despite considerable work to understand and reverse declines attributable to introduced predators and fisheries bycatch, pollution is an oft-cited threat to these species. Presently, toxicological research, including the establishment of baseline concentrations and time series, is still nascent. Pb toxicity warrants further investigation as predation may not be the only threat present. All species in this study are well above the provisional Se LOAEL and did not display any observable effects of toxicity at the time of sample collection. Similar findings have been reported for critically endangered albatross (Cherel et al. 2018), prompting a call for robust assessment of the impact of metal/metalloid exposure on the physiology and demography of seabirds in light of increasing inputs of chemicals into our oceans. Therefore, we recommend further investigation into what concentration of Se should be used as a LOAEL in *Pterodroma* species, and whether there is a risk to the health of the species included in this study from the toxicity of Pb and Se.

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