A Global Overview of Exposure Levels and Biological Effects of Trace Elements in Penguins

Chapter *in* Reviews of environmental contamination and toxicology · September 2017

DOI: 10.1007/398_2017_5

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A Global Overview of Exposure Levels and Biological Effects of Trace Elements in Penguins

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Reviews of Environmental Contamination and Toxicology,
DOI 10.1007/398_2017_5

Acronyms

Al	Aluminum
As	Arsenic
Ca	Calcium
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
Hg	Mercury
Mn	Manganese
Ni	Nickel
Pb	Lead
Se	Selenium
V	Vanadium
Zn	Zinc

Highlights

- Most of the studies of metals in penguins have been carried out in Antarctic and subantarctic islands. However, there is a lack of data from lower latitudes where other important penguin species inhabit.
- The levels of metals are reported mainly in feathers and excreta. Further research in other biological matrices such as internal organs and blood is required.
- Further research in the issue of biological effects caused by metals is needed.
- Little is known about the interaction among the metals which could activate certain mechanisms of detoxification of the body of the penguins.

1 Introduction

Trace metal toxicity is one of the major stressors leading to hazardous effects on biota (Bargagli 2001; Zhang and Ma 2011). In aquatic environments, trace element contamination is a great concern, due to the implications these chemicals may have on both wildlife and human health (Lavoie et al. 2013; Prashanth et al. 2016). These elements enter the water through natural erosion, geochemical cycles, industrial processes, and agricultural practices (Burger and Gochfeld 2000a). In birds, some metals can produce severe adverse effects such as difficulty in flying, walking and standing, paralysis, and an increase in mortality (Newman 2015). In order to monitor the occurrence of environmental pollutants in marine ecosystems, the use of aquatic birds has greatly increased, because they can accumulate trace elements in diverse tissues, such as eggs, feathers, or liver, thus can be used to indirectly evaluate in a proper way the toxicological status of the marine ecosystem under study (Savinov et al. 2003). Moreover, seabird diet and feeding ecology can differ in response to climate change, thus affecting exposure to metals over time (Braune et al. 2014). Evidence indicates that the concentrations of certain pollutants in seabirds have a lower variation coefficient than that observed in fishes or marine mammals, so that the analysis of a relatively low number of samples of birds is similar to that obtained by analyzing a significantly higher number in other groups of animals (Pérez-López et al. 2005). Birds tend to be more sensitive to environmental contaminants than other vertebrates (Zhang and Ma 2011), thus ecotoxicological studies on seabirds have proliferated in recent years (Casini et al. 2001; Barbieri et al. 2010; Barbosa et al. 2013; Celis et al. 2014; Kehrig et al. 2015).

The study of trace elements in penguins is valuable, because they are animals that exclusively inhabit the Southern Hemisphere and represent about 90% of the bird biomass of the Southern Ocean (Williams 1990). Penguins are present in different systems in the Antarctic, subantarctic islands of the Pacific, Atlantic, and Indian oceans, as well as on the coasts of Australia, South Africa, South America, and the Galapagos (García and Boersma 2013). Penguins are useful indicators of the degree of contamination by trace elements in the environment, because they are highly specialized animals that swim and dive in search for food, are widely distributed, and are organisms usually found at the top of the trophic web (De Moreno et al. 1997; Boersma 2008; Fig. 1). Additionally, penguins are extremely interesting as bioindicators because of their intense molting process (Carravieri et al. 2014), and because they can be finicky eaters with a restricted diet (Lescroël et al. 2004; Jerez et al. 2011).

The different penguin species (order Sphenisciformes, family Spheniscidae) can be classified in the genera *Aptenodytes*, *Eudyptes*, *Eudyptula*, *Megadyptes*, *Pygoscelis,* and *Spheniscus*. These species have in common the fact of presenting serious risks of survival in the future, because about two thirds of penguin species are on the Red List of Threatened Species of the International Union for Conservation of Nature (UICN 2016). Contamination, climate change, fishing, alterations of ecosystems, diseases, and even tourism are their major threats (García and Boersma 2013). The lack of knowledge about the effects of trace elements in seabirds is a main threat to their population sustainability (Sanchez-Hernandez 2000).

The study of the biological effects of toxic trace elements ingested by penguins is of great relevance because it may contribute knowledge of possible consequences in nature (Nordberg and Nordberg 2016). Moreover, evidence has revealed that some trace elements such as As, Cd, Hg, Mn, Pb, and Zn can affect the endocrine system of animals and humans, producing alterations in physiological functions (Iavicoli et al. 2009). Given the wide distribution of penguins, data concerning trace element concentrations in different biotic matrices of penguins are summarized

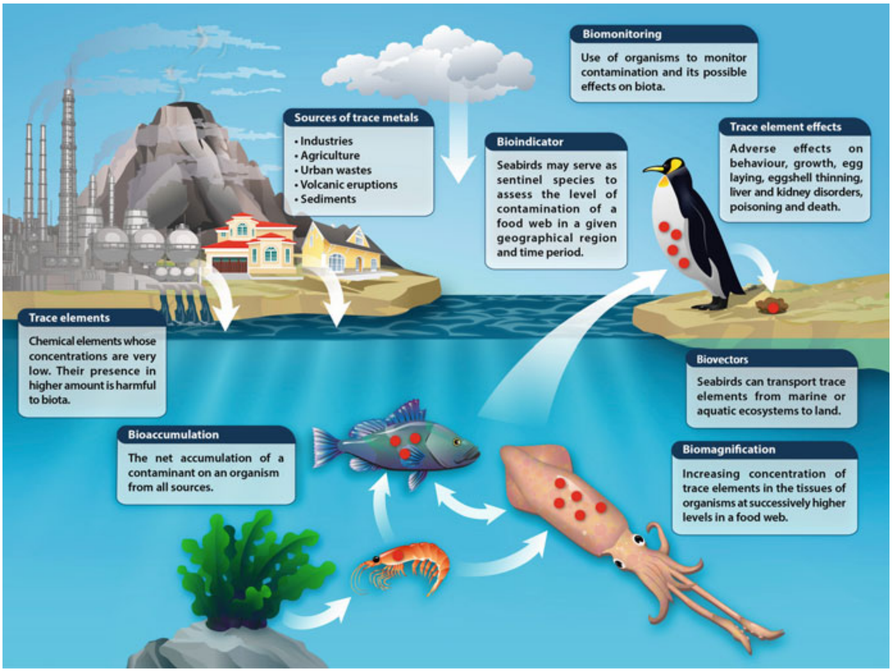

Fig. 1 Sources of trace elements in the environment, bioaccumulation, biomagnification, and effects on penguins. According to Newman (2015), bioaccumulation is the net accumulation of a contaminant on an organism from all sources including water, air, and solid phases (food, soil, sediment, or fine particles suspended in air or water) in the environment. Biomonitoring is the use of organisms to monitor contamination and its possible effects on biota (at individual level, population, or communities) and ecosystems

here to be used as a first background database for contamination detection in marine ecosystems.

2 Materials and Methods

In order to identify the interaction of penguin species and trace elements, a systematic study of the existing literature on the concentrations of trace elements in different biotic matrices studied was conducted. These biological matrices correspond to guano, feathers, eggs, blood, stomach contents, and internal organs. By using databases such as Direct, Springer, Scopus, and Web of Science, different keywords were used. Among them, “trace element,” “heavy metal,” “trace metals,” “mercury,” “aluminum,” “arsenic,” “cadmium,” “lead,” “zinc,” “copper,” “pollution,” “persistent pollutants,” “monitoring,” “biomonitoring,” “penguin,” “seabirds,” “eggs,” “blood,” “guano,” “droppings,” “feathers,” “tissues,” “organs,” and “Antarctic” can be mentioned. Furthermore, the list of references of each publication was reviewed to identify additional documents on the issue not previously found. Selection criteria strictly corresponded to trace element concentrations on the basis of dry weight (dw) based on studies performed in situ.

Subsequently this information was summarized in tables. Mean levels of exposure to trace elements in penguins were compared with other marine, aquatic, or terrestrial birds from different parts of the world. In addition, maps of the distribution of penguins were included along with records of trace elements, based on the identification of the different colonies of penguins worldwide (Boersma 2008). Information about the investigations related to the exposure and effect of trace elements in penguins was also considered.

A bubble chart was built upon mean concentrations of each trace element reported in gentoo penguins (*Pygoscelis papua*) at South Shetland Islands to see similarities and differences according to biological matrices. First, concentration values were normalized by log (x + 1) to remove any weighting from dominant peaks and then analyzed with a Bray-Curtis similarity matrix (Clarke et al. 2006). Finally, the resultant similarity matrix was analyzed in a two-dimensional multidimensional scaling (MDS) plot.

Values of the trophic transference coefficient (TTC), as the ratio between the level of a certain element in the penguin's body (liver, kidneys, bones, and muscles together) and the level of the element in stomach contents (Suedel et al. 1994), were calculated taking into consideration the mean concentration of each element.

3 Exposure to Trace Elements and Its Effects on Penguins

Trace element concentrations measured in different biotic matrices of different species of penguins are presented in Tables 1, 2, 3, 4, 5, 6, 7, 8, and 9. The most commonly reported trace elements in penguins are Al, As, Cd, Cu, Hg, Mn, Pb, and Zn, whereas the gentoo penguin is the species that displays the highest concentration of most trace elements studied. Other trace elements such as Co, Cr, Fe, Ni, and Se have been poorly studied (Szopińska et al. 2016). Levels of Fe (23.37–164.26 μg/g) have been reported in feathers of pygoscelid penguins from Antarctica (Metcheva et al. 2006; Jerez et al. 2011). In the same matrix and region, levels of Se (1.8–2.0 μg/g) have been linked with a major exposure to Cd and Hg (Jerez et al. 2011), since Se is known to have a detoxifying effect of these metals (Smichowski et al. 2006). Cobalt levels have been reported in feathers of chinstrap and gentoo penguins from Antarctica (0.17–0.25 μg/g, Metcheva et al. 2006). Nickel has been reported in chinstrap penguins from Antarctica in feces (3.2–3.7 μg/g), liver (0.07 μg/g), and muscle (<0.03 μg/g) by Metcheva et al. (2006), and in feathers of pygoscelid penguins (0.24–1.18 μg/g, Jerez et al. 2011). In the organs of most avian wildlife species from unpolluted ecosystems, Ni concentrations may vary greatly (0.1–2.0 μg/g, Outridge and Scheuhammer 1993). Chromium levels (1.15–8.08 μg/g) were reported by Jerez et al. (2011) in

Table 1 Mean trace metal levels (μg/g, dw) in feathers of different penguin species worldwide

Species	N	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
P. adeliae	3	–	–	–	–	0.82±0.13	–	–	–	Terra Nova Bay[b]	1989–1990	Bargagli et al. (1998)
	1	–	–	–	–	1.40	–	61.5	–	Admiralty Bay[c]	2004	Santos et al. (2006)
	n/i	–	–	–	1.50	0.60	–	–	–	Zhongshan Station[d]	2001	Yin et al. (2008)
	1	3.56	0.04	0.12	<0.01	–	16.21	70.41	0.21	King George is.[c]	2007–2010	Jerez et al. (2013a)
	2	0.71±0.43	0.06±0.001	0.08±0.01	0.06±0.09	–	16.22±0.51	60.59±2.02	<0.01	Avian is.[e]	2007–2010	Jerez et al. (2013a)
	1[f]	52.44	0.08	0.01	<0.01	–	19.29	83.90	1.15	King George is.[c]	2007–2010	Jerez et al. (2013a)
	5	64.3±61.75	0.17±0.11	0.13±0.08	0.24±0.38	–	13.32±8.22	61.11±20.3	2.01±0.52	King George is.[c]	2008–2009	Jerez et al. (2013b)
	4	–	–	0.30	0.50	0.90	–	–	–	Edmonson Point[b]	1995	Ancora et al. (2002)
	25	43.36±69.03	–	–	0.64±1.09	–	12.68±7.09	50.84±17.38	1.30±1.16	King George is.[c]	2005–2007	Jerez et al. (2011)
	21	8.62±6.41	0.07±0.04	0.04±0.05	0.32±0.36	–	13.41±2.6	82.45±13.1	1.16±1.26	Yalour is.[e]	2005–2007	Jerez et al. (2011)
	22	5.08±3.03	0.07±0.03	0.04±0.02	0.14±0.21	–	13.16±3.04	77.69±15.17	0.34±0.49	Avian is.[e]	2005–2007	Jerez et al. (2011)
	10	–	–	–	–	0.66±0.2	–	–	–	Adélie land[g]	2007	Carravieri et al. (2016)

	12	–	–	–	–	0.43±0.13	–	–	–	Adélie land[g]	2006	Carravieri et al. (2016)
	10[f]	–	–	–	–	0.19±0.06	–	–	–	Adélie land[g]	2007	Carravieri et al. (2016)
P. antarctica	25	132.4±198.09	0.10	–	1.76±1.74	–	20.29±8.3	77.12±45.15	1.66±0.98	King George is.[c]	2007	Jerez et al. (2011)
	10	26.07±9.97	0.01±0.0001	0.04±0.03	0.15±0.12	–	14.93±6.1	72.21±28.96	0.92±0.59	Livingston is.[c]	2000	Jerez et al. (2011)
	25	203.13±194.65	0.10±0.1	0.08±0.04	0.32±0.22	–	16.39±3.44	82.40±15.64	3.26±2.68	Deception is.[c]	2005–2007	Jerez et al. (2011)
	20	14.26±9.72	0.05±0.03	0.10±0.05	0.14±0.09	–	19.23±3.65	97.27±21.35	0.29±0.39	Ronge is.[e]	2005–2007	Jerez et al. (2011)
	3	8.99±7.86	0.07±0.01	0.31±0.22	0.81±0.84	–	19.60±1.7	62.29±20.01	0.05±0.03	Deception is.[c]	2005–2007	Jerez et al. (2013a)
	2	7.99±10.02	0.31±0.21	0.01±0.01	0.02±0.03	–	15.29±0.34	94.75±2.37	0.21±0.30	King George is.[c]	2005–2007	Jerez et al. (2013a)
	5	142±206.33	0.48±0.3	0.02±0.03	0.06±0.04	–	18.57±2.78	94.99±5.29	2.25±3.17	Deception is.[c]	2007–2010	Jerez et al. (2013b)
	29	26±8	0.45±0.2	0.30±0.07	1.73±0.94	–	18.5±3	87.0±5	1.5±0.7	Livingston is.[c]	2007–2010	Metcheva et al. (2006)
	32	26±11	2.4[a]	0.2[a]	1.66±1.2	–	18±2	75±7	1.6±0.43	Livingston is.[c]	2008–2009	Metcheva et al. (2006)
P. papua	1	–	–	–	–	0.54	–	90.70	–	Admiralty Bay[c]	2002	Santos et al. (2006)
	14	40±10	0.88±0.32	0.21±0.06	1.7±1.3	–	17±4	106±8	1.5±0.73	Livingston is.[c]	2002	Metcheva et al. (2006)

(continued)

Table 1 (continued)

Species	N	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
	28	46±22	(<0.6–4.0)[h]	(0.15–0.43) [h]	1.57±1.13	–	16±2	89±7	2.6±0.99	Livingston is.[c]	2003	Metcheva et al. (2006)
	1[i]	–	–	0.50±0.12	<1.90	–	15.9±0.12	73.0±0.54	1.65±0.15	Livingston is.[c]	2002–2006	Metcheva et al. (2010)
	14	37.0±6.9	(0.3–0.69) [h]	(0.05–0.41) [h]	1.52±0.5	–	17.0±3.1	92.0±4.6	1.70±0.2	Livingston is.[c]	2006–2007	Metcheva et al. (2011)
	20	39.76±24.74	0.05±0.04	0.03±0.03	0.51±0.46	–	16.44±3.16	85.12±14.84	1.80±1.28	King George is.[c]	2005–2007	Jerez et al. (2011)
	14	40.17±42.37	0.02±0.02	0.02±0.01	0.17±0.23	–	13.88±2.89	75.41±15.85	1.17±1.05	Livingston is.[c]	2005–2007	Jerez et al. (2011)
	17	22.92±27.87	0.04±0.02	0.03±0.01	0.25±0.44	–	16.02±2.09	72.89±7.46	0.46±0.58	Ronge is.[e]	2005–2007	Jerez et al. (2011)
	8	17.19±11.9	0.07	0.03±0.04	0.31±0.09	–	13.42±5.09	61.71±18.01	0.68±0.66	Paradise Bay [e]	2005–2007	Jerez et al. (2011)
	11	–	–	–	–	5.90±1.91[j]	–	–	–	Crozet is.[k]	2007	Carravieri et al. (2016)
	12	–	–	–	–	5.23±1.12	–	–	–	Crozet is.[k]	2006	Carravieri et al. (2016)
	12[l]	–	–	–	–	1.88±0.46	–	–	–	Crozet is.[k]	2007	Carravieri et al. (2016)
	4[f]	15.72±19.24	0.09±0.07	0.02±0.01	0.07±0.13	–	16.02±5.40	119.72±21.81	0.27±0.35	King George is.[c]	2007–2010	Jerez et al. (2013a)
	2	6.71±5.15	0.10±0.05	0.02±0.004	0.33±0.31	–	19.26±0.94	69.49±6.32	0.06±0.09	King George is.[c]	2007–2010	Jerez et al. (2013a)

	5	68.55±76.39	0.12±0.05	0.06±0.04	0.87±0.86	–	6.87±1.54	80.59±10.85	0.95±0.69	King George is.[c]	2008–2009	Jerez et al. (2013b)
	10	–	–	0.05±0.07	0.06±0.04	–	13.74±1.81	36.89±6.26	0.75±0.28	Neko Harbor[e]	2014	Celis et al. (2015b)
	10	–	–	0.09±0.07	0.10±0.17	–	14.98±4.09	33.26±4.04	0.27±0.37	Doumer is.[e]	2014	Celis et al. (2015b)
	10	–	–	0.14±0.09	0.60±0.34	–	19.65±2.25	64.19±10.67	1.23±0.46	Stranger Point[c]	2014	Celis et al. (2015b)
	10	–	–	0.21±0.28	0.63±0.27	–	20.89±4.3	64.07±10.73	1.19±0.68	O´Higgins Base[e]	2014	Celis et al. (2015b)
	55	–	–	–	–	0.97±0.67	–	–	–	South Georgia[d]	2009	Pedro et al. (2015)
	29	–	–	–	–	1.1±0.62	–	–	–	South Georgia[d]	2011	Pedro et al. (2015)
	12	–	–	–	–	5.85±3.00	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12	–	–	–	–	4.96±2.44	–	–	–	Kerguelen is.[k]	2006	Carravieri et al. (2013)
	12[l]	–	–	–	–	2.45±0.67	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12	–	–	–	–	1.44±0.44	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
A. forsteri	3	–	–	–	–	0.98±0.21	–	–	–	Terra Nova Bay[b]	1989–1990	Bargagli et al. (1998)
	17	–	–	–	–	1.77±0.37	–	–	–	Adélie Land[g]	2007	Carravieri et al. (2016)

(continued)

Table 1 (continued)

Species	N	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
	12[f]	–	–	–	–	0.61±0.11	–	–	–	Adélie Land[g]	2007	Carravieri et al. (2016)
A. patagonicus	31	–	–	–	–	1.98±0.73	–	–	–	Crozet is.[k]	2000–2001	Scheifler et al. (2005)
	10	–	–	–	–	2.66±0.86	–	–	–	Crozet is.[k]	1966–1974	Scheifler et al. (2005)
	12	–	–	–	–	2.22±0.59	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12	–	–	–	–	2.17±0.52	–	–	–	Kerguelen is.[k]	2006	Carravieri et al. (2013)
	12[f]	–	–	–	–	1.79±0.55	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12[l]	–	–	–	–	1.12±0.16	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12	–	–	–	–	2.94±0.47	–	–	–	Crozet is.[k]	2006	Carravieri et al. (2016)
	12	–	–	–	–	2.89±0.73	–	–	–	Crozet is.[k]	2007	Carravieri et al. (2016)
	12[f]	–	–	–	–	1.80±0.24	–	–	–	Crozet is.[k]	2007	Carravieri et al. (2016)

E. chrysolophus	12	–	–	–	–	2.24±0.29	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12	–	–	–	–	2.08±0.35	–	–	–	Kerguelen is.[k]	2006	Carravieri et al. (2013)
	12[l]	–	–	–	–	0.36±0.07	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12	–	–	–	–	2.48±0.35	–	–	–	Crozet is.[k]	2007	Carravieri et al. (2016)
	12	–	–	–	–	2.09±0.31	–	–	–	Crozet is.[k]	2006	Carravieri et al. (2016)
	12[f]	–	–	–	–	0.43±0.10	–	–	–	Crozet is.[k]	2007	Carravieri et al. (2016)
S. magellanicus	21	–	–	–	–	0.206±0.098	–	–	–	Punta Tombo [m]	2007	Frias et al. (2012)
	18[n]	–	–	–	–	0.123±102	–	–	–	Punta Tombo [m]	2007	Frias et al. (2012)
	37[f]	–	–	–	–	0.033±0.052	–	–	–	Punta Tombo [m]	2007	Frias et al. (2012)
	22	–	–	0.13±0.07	0.14±0.08	0.78±0.44	–	–	–	Rio Grande do Sul[o]	n/i	Kehrig et al. (2015)
E. chrysocome	12	–	–	–	–	1.96±0.41	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12	–	–	–	–	1.92±0.35	–	–	–	Kerguelen is.[k]	2006	Carravieri et al. (2013)

(continued)

Table 1 (continued)

Species	N	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
	12[f]	–	–	–	–	0.27±0.06	–	–	–	Kerguelen is.[k]	2007	Carravieri et al. (2013)
	12	–	–	–	–	1.79±0.37	–	–	–	Crozet is.[k]	2007	Carravieri et al. (2016)
	12	–	–	–	–	1.62±0.35	–	–	–	Crozet is.[k]	2006	Carravieri et al. (2016)
	12[f]	–	–	–	–	0.34±0.05	–	–	–	Crozet is.[k]	2007	Carravieri et al. (2016)
E. minor	13	40.38±22.96	0.16±0.05	0.04±0.02	0.42±0.20	4.13±0.98	11.42±2.19	84.77±11.28	–	St. Kilda [p]	2012	Finger et al. (2015)
	12	16.78±16.11	0.18±0.1	0.04±0.03	0.08±0.03	2.70±0.37	10.77±1.5	80.58±8.06	–	Phillip is.[p]	2012	Finger et al. (2015)
	10	6.25±2.79	0.09±0.03	0.06±0.02	0.10±0.05	1.50±0.82	10.54±2.07	76.80±7.15	–	Notch is.[p]	2012	Finger et al. (2015)
E. moseleyi	12	–	–	–	–	2.10±0.36	–	–	–	Amsterdam is.[q]	2006	Carravieri et al. (2016)
	12	–	–	–	–	1.82±0.30	–	–	–	Amsterdam is.[q]	2007	Carravieri et al. (2016)
	15[f]	–	–	–	–	0.34±0.07	–	–	–	Amsterdam is.[q]	2007	Carravieri et al. (2016)

n/*i* not informed

(continued)

[a]Sample collection
[b]Victoria Land (East Antarctica)
[c]South Shetland Islands (West Antarctica)
[d]Subantarctic area of the Atlantic Ocean
[e]Several locations of the Antarctic Peninsula (West Antarctica)
[f]Juvenile
[g]East Antarctica
[h]Authors only report min and max values
[i]Duplicates were performed from the sample
[j](Max 8.16 μg/g)
[k]South East of Indian Ocean
[l]Chicks
[m]Coast of Argentina
[n]Young adults
[o]Coast of Brazil
[p]Victoria, Australia
[q]Southern of the Indian Ocean
[r]Mirror Peninsula (East Antarctica)

Table 2 Mean trace metal levels (µg/g, dw) measured in eggshells of different penguin species

Species	*N*	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
P. adeliae	13	–	–	–	–	0.26 ± 0.08	–	–	–	Terra Nova Bay[b]	1989–1990	Bargagli et al. (1998)
	89	–	–	–	–	0.02 ± 0.01	–	–	–	King George is.[c]	2006–2011	Brasso et al. (2014)
	1	–	–	–	–	0.005	–	8.30	–	Admiralty Bay[c]	2004	Santos et al. (2006)
P. antarctica	92	–	–	–	–	0.07 ± 0.05	–	–	–	King George is.[c]	2006–2011	Brasso et al. (2014)
P. papua	n/i	–	–	–	0.75	0.05	–	–	–	Fildes Peninsula[c]	2002	Yin et al. (2008)
	12	28.96 ± 4.3	<0.3	<0.05	0.68 ± 0.3	–	1.24 ± 0.4	4.07 ± 0.6	0.82 ± 0.08	Livingston is.[c]	2006–2007	Metcheva et al. (2011)
	90	–	–	–	–	0.02 ± 0.01	–	–	–	King George is.[c]	2006	Brasso et al. (2014)

n/i not informed
[a]Sample collection
[b]Victoria Land (East Antarctica)
[c]South Shetland Islands (West Antarctica)

Table 3 Mean trace metal levels (μg/g, dw) in bones of different penguin species

Species	*N*	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
P. adeliae	n/i	–	–	–	1.60	0.02	–	–	–	Zhongshan Station[b]	2001	Yin et al. (2008)
	1	8.49	0.07	0.03	<0.001	–	0.06	138.38	7.44	King George is.[c]	2007–2010	Jerez et al. (2013a)
	1	5.61	0.12	0.17	0.10	–	0.17	106.15	7.56	Avian is.[d]	2007–2010	Jerez et al. (2013a)
	5	11.89 ± 3.69	0.13 ± 0.08	0.01 ± 0.004	0.04 ± 0.1	–	0.96 ± 0.53	227.01 ± 121.11	8.31 ± 3.11	King George is.[c]	2008–2009	Jerez et al. (2013b)
P. antarctica	2	4.16 ± 1.02	0.08 ± 0.07	<0.001	<0.001	–	0.17 ± 0.22	221.3 ± 9.19	6.66 ± 0.57	King George is.[c]	2007–2010	Jerez et al. (2013a)
	4	7.30 ± 6.09	0.04 ± 0.01	0.07 ± 0.03	0.21 ± 0.12	–	0.19 ± 0.1	138.77 ± 20.63	8.40 ± 1.25	Deception is. [c]	2007–2010	Jerez et al. (2013a)
	5	7.38 ± 2.93	0.14 ± 0.13	0.004 ± 0.001	0.14 ± 0.02	–	0.71 ± 0.36	235.01 ± 40.62	12.5 ± 2.13	Deception is. [c]	2008–2009	Jerez et al. (2013b)
P. papua	1	69.95	0.13	0.001	0.19	–	0.79	184.1	11.01	King George is.[c]	2008–2009	Jerez et al. (2013b)
	13	32.28 ± 14.96	0.19 ± 0.04	0.008 ± 0.003	<0.001	–	1.15 ± 0.33	244.6 ± 7.99	18.35 ± 2.28	Byers peninsula[c]	2009	Barbosa et al. (2013)
	8	18.63 ± 4.44	0.12 ± 0.01	0.005 ± 0.001	0.02 ± 0.01	–	0.74 ± 0.09	223.82 ± 21.91	9.81 ± 1.21	Hannah point[c]	2009	Barbosa et al. (2013)
	2	7.59 ± 0.2	0.06 ± 0.01	0.002 ± 0.002	0.15 ± 0.19	–	0.20 ± 0.11	180.05 ± 29.4	8.27 ± 1.78	King George is.[c]	2007–2010	Jerez et al. (2013a)
	1[e]	–	–	0.10 ± 0.02	0.30 ± 0.14	–	0.90 ± 0.028	81 ± 0.6	2.50 ± 0.23	Livingston is.[c]	2002–2006	Metcheva et al. (2010)

[a]Sample collection
[b]Mirror Peninsula (East Antarctica)
[c]South Shetland Islands (West Antarctica)
[d]Southern of the Antarctic Peninsula
[e]Duplicates were performed from the sample

Table 4 Mean trace metal levels (μg/g, dw) in kidneys of different penguin species

Species	N	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
P. adeliae	1	–	–	–	–	1.20	–	–	–	Terra Nova Bay[b]	1989–1990	Bargagli et al. (1998)
	1	0.74	1.07	54.41	<0.01	–	10.74	163.71	3.78	King George is.[c]	2007–2010	Jerez et al. (2013a)
	1[d]	3.48	0.45	0.68	<0.01	–	12.66	119.90	7.79	King George is.[c]	2007–2010	Jerez et al. (2013a)
	2	14.12 ± 3.86	0.38 ± 0.12	351.8 ± 0.08	0.21 ± 0.17	–	14.78 ± 3.04	234.3 ± 62.24	5.77 ± 1.36	Avian is.[e]	2007–2010	Jerez et al. (2013a)
	5	4.09 ± 7.05	0.44 ± 0.24	0.20 ± 0.15	0.05 ± 0.12	–	11.85 ± 3.69	85.74 ± 19.49	11.18 ± 6.12	King George is.[c]	2008–2009	Jerez et al. (2013b)
	3	–	0.547 ± 0.033	0.339 ± 0.012	0.144 ± 0.007	0.146 ± 0.004	1.6 ± 0.12	–	9.4 ± 0.2	Potter Cove[f]	2002–2003	Smichowski et al. (2006)
	5	–	–	263.8 ± 216.6	–	–	17.80 ± 4.1	–	–	Weddell Sea[g]	1982–1983	Steinhagen-Schneider (1986)
P. antarctica	2	0.69 ± 0.38	0.52 ± 0.6	0.49 ± 0.32	<0.01	–	17.13 ± 2.63	107.79 ± 23.57	10.13 ± 2.37	King George is.[c]	2007–2010	Jerez et al. (2013a)
	4	0.75 ± 0.76	0.58 ± 0.12	263.93 ± 139.77	0.18 ± 0.01	–	15.33 ± 4.67	149.8 ± 49.23	5.35 ± 0.75	Deception is.[c]	2007–2010	Jerez et al. (2013a)
	5	10.93 ± 10.57	0.50 ± 0.09	0.54 ± 0.29	0.14 ± 0.02	–	13.64 ± 2.28	92.83 ± 32.19	10.19 ± 2.63	Deception is.[c]	2008–2009	Jerez et al. (2013b)
A. forsteri	4	–	–	270.2 ± 126.8	–	–	19.1 ± 3.0	–	–	Weddell Sea[g]	1982–1983	Steinhagen-Schneider (1986)
P. papua	3	2.13 ± 0.62	0.67 ± 0.41	11.37 ± 14.1	0.07 ± 0.03	–	13.99 ± 2.91	93.14 ± 42.13	6.40 ± 3.07	King George is.[c]	2007–2010	Jerez et al. (2013a)
	4[d]	4.8 ± 4.24	0.43 ± 0.17	1.54 ± 0.71	<0.01	–	19.99 ± 6.83	152.14 ± 18.51	7.33 ± 3.38	King George is.[c]	2007–2010	Jerez et al. (2013a)
	5	6.91 ± 3.95	0.40 ± 0.23	0.20 ± 0.05	<0.001	–	14.26 ± 4.33	125.43 ± 12.60	7.54 ± 3.47	King George is.[c]	2008–2009	Jerez et al. (2013b)
	1[h]	–	–	41.20 ± 0.67	0.10 ± 0.5	–	8.10 ± 0.45	232.0 ± 2.67	4.90 ± 0.44	Livingston is.[c]	2002–2006	Metcheva et al. (2010)
S. magellanicus	22	–	–	46.50 ± 33.55	0.55 ± 0.3	2.47 ± 1.42	–	–	–	Rio Grande do Sul[i]	n/i	Kehrig et al. (2015)

[a]Sample collection
[b]Victoria Land (East Antarctica)
[c]South Shetland Islands (West Antarctica)
[d]Juvenile
[e]Several locations of the Antarctic Peninsula
[f]King George Island (South Shetland Islands, West Antarctica)
[g]Northeast of the Antarctic Peninsula
[h]Duplicates were performed from the sample
[i]Coast of Brazil

Table 5 Mean trace metal levels (μg/g, dw) in liver of different penguin species

Species	*N*	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
P. adeliae	1	4.19	1.20	4.41	0.05	–	10.91	136.3	8.58	King George is.[b]	2007–2010	Jerez et al. (2013a)
	2	0.55 ± 0.11	0.33 ± 0.04	22.03 ± 10.47	0.06 ± 0.03	–	15.34 ± 1.87	141.75 ± 4.21	11.55 ± 4.55	Avian is.[c]	2007–2010	Jerez et al. (2013a)
	1[d]	1.93	0.30	0.18	<0.01	–	22.89	182.58	15.83	King George is.[b]	2007–2010	Jerez et al. (2013a)
	5	6.81 ± 11.91	0.60 ± 0.4	0.06 ± 0.05	0.04 ± 0.07	–	92.06 ± 74.53	133.88 ± 71.42	12.01 ± 5.8	King George is.[b]	2008–2009	Jerez et al. (2013b)
	3	–	0.499 ± 0.024	0.102 ± 0.007	0.202 ± 0.009	0.269 ± 0.01	18.0 ± 1.0	–	10.0 ± 0.2	Potter Cove[e]	2002–2003	Smichowski et al. (2006)
	3	–	–	7.20 ± 0.12	0.30 ± 0.05	–	11.90 ± 0.5	140.0 ± 4	6.80 ± 0.2	AP[f]	1989	Szefer et al. (1993)
	5	–	–	7.50 ± 2.4	–	–	19.90 ± 5.8	–	–	Weddell Sea[g]	1982–1983	Steinhagen-Schneider (1986)
P. antarctica	2	1.0 ± 0.14	0.37 ± 0.36	0.16 ± 0.08	0.05 ± 0.01	–	24.26 ± 11.18	330.34 ± 293.26	14.76 ± 4.17	King George is.[b]	2007–2010	Jerez et al. (2013a)
	4	2.02 ± 1.47	0.67 ± 0.15	27.54 ± 14.47	0.15 ± 0.06	–	14.95 ± 0.67	126.05 ± 25.18	9.30 ± 2.06	Deception is.[b]	2007–2010	Jerez et al. (2013a)
	5	15.52 ± 15.55	0.47 ± 0.14	0.11 ± 0.08	0.18 ± 0.02	–	95.10 ± 48.67	132.2 ± 64.4	11.42 ± 3.24	Deception is.[b]	2008–2009	Jerez et al. (2013b)
	3	–	–	10.70 ± 0.3	0.01	–	12.60 ± 0.4	126.0 ± 1	7.50 ± 0.5	AP[f]	1989	Szefer et al. (1993)
A. forsteri	4	–	–	27.7 ± 15.6	–	–	23.4 ± 4.0	–	–	Weddell Sea[g]	1982–1983	Steinhagen-Schneider (1986)
P. papua	3	2.19 ± 0.52	1.01 ± 0.9	1.05 ± 1.43	0.10 ± 0.07	–	102.57 ± 155.93	112.56 ± 72.69	7.71 ± 6.34	King George is.[b]	2007–2010	Jerez et al. (2013a)
	4[d]	1.62 ± 1	0.79 ± 0.63	0.40 ± 0.18	<0.01	–	386.13 ± 174.48	237.19 ± 22.38	8.30 ± 0.57	King George is.[b]	2007–2010	Jerez et al. (2013a)
	5	2.12 ± 2.05	0.45 ± 0.18	0.08 ± 0.04	<0.001	–	142.4 ± 63.85	152.91 ± 45.53	10.51 ± 3.74	King George is.[b]	2008–2009	Jerez et al. (2013b)
	3	–	–	3.19 ± 0.1	0.48 ± 0.12	–	26.50 ± 0.9	100.0 ± 4	8.80 ± 0.8	AP[f]	1989	Szefer et al. (1993)

	1[h]	–	–	2.32 ± 0.27	0.50	–	24.70 ± 0.19	72 ± 0.53	7.10 ± 0.17	Livingston is.[b]	2002–2006	Metcheva et al. (2010)
S. magellanicus	22	–	–	7.25 ± 4.71	0.58 ± 0.32	5.70 ± 3.73	–	–	–	Rio Grande do Sul[i]	n/i	Kehrig et al. (2015)

[a]Sample collection
[b]South Shetland Islands (West Antarctica)
[c]Antarctic Peninsula
[d]Juvenile
[e]King George Island (South Shetland Islands, West Antarctica)
[f]Several locations of the Antarctic Peninsula
[g]Northeast of the Antarctic Peninsula
[h]Duplicates were performed from the sample
[i]Coast of Brazil

Table 6 Mean trace metal levels (μg/g, dw) in muscles of different penguin species

Species	*N*	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
P. adeliae	1	–	–	–	–	0.6	–	–	–	Terra Nova Bay[b]	1989	Bargagli et al. (1998)
	1	3.27	0.37	1.09	<0.01	–	7.43	149.95	0.63	King George is.[c]	2007–2010	Jerez et al. (2013a)
	2	1.78 ± 1.91	0.30 ± 0.16	2.63 ± 2.09	0.15 ± 0.11	–	8.53 ± 2.41	66.26 ± 57.77	1.11 ± 0.39	Avian is.[d]	2007–2010	Jerez et al. (2013a)
	1[e]	3.41	0.18	<0.01	<0.01	–	6.97	163.75	0.91	King George is.[b]	2007–2010	Jerez et al. (2013a)
	5	6.14 ± 6.72	0.39 ± 0.25	0.01 ± 0.02	0.04 ± 0.01	–	5.52 ± 1.97	104.34 ± 49.7	1.13 ± 0.4	King George is.[b]	2008–2009	Jerez et al. (2013b)
	3	–	0.815 ± 0.007	<0.001	0.12 ± 0.007	–	6.4 ± 0.4	–	1.50 ± 0.1	Potter Cove[f]	2002–2003	Smichowski et al. (2006)
	9	–	–	0.46 ± 0.42	0.04 ± 0.01	–	7.90 ± 0.7	46.7 ± 10	0.51 ± 0.16	AP[g]	1989	Szefer et al. (1993)
	5	–	–	0.32 ± 0.02	–	–	8.20 ± 2.4	–	–	Weddell Sea[h]	1982	Steinhagen-Schneider (1986)
P. antarctica	2	1.07 ± 0.36	0.57 ± 0.62	0.01 ± 0.001	<0.01	–	8.07 ± 1.28	139.91 ± 40.94	0.87 ± 0.28	King George is.[c]	2007–2010	Jerez et al. (2013a)
	4	12.32 ± 10.04	1.04 ± 0.27	1.83 ± 0.63	0.17 ± 0.08	–	6.69 ± 1.73	118.8 ± 40.73	1.17 ± 0.68	Deception is.[c]	2007–2010	Jerez et al. (2013a)
	5	114.88 ± 125.59	0.59 ± 0.3	0.01 ± 0.01	0.20 ± 0.06	–	6.82 ± 1.2	105.08 ± 55.41	2.55 ± 1.53	Deception is.[c]	2008–2009	Jerez et al. (2013b)
	3	–	–	0.57 ± 0.02	0.01	–	9.70 ± 0.3	37.0 ± 2.9	0.76 ± 0.31	AP[g]	1989	Szefer et al. (1993)
P. papua	3	1.39 ± 0.95	0.63 ± 0.53	0.11 ± 0.18	0.18 ± 0.05	–	7.97 ± 1.15	103.07 ± 60.55	0.85 ± 0.39	King George is.[c]	2007–2010	Jerez et al. (2013a)
	4[e]	2.01 ± 1.96	0.36 ± 0.21	0.01 ± 0.01	<0.01	–	9.95 ± 2.08	139.39 ± 46.68	0.52 ± 0.06	King George is.[c]	2007–2010	Jerez et al. (2013a)
	5	43.71 ± 21.93	0.40 ± 0.23	0.01 ± 0.01	<0.001	–	4.43 ± 1.46	106.6 ± 37.42	1.46 ± 0.43	King George is.[c]	2008–2009	Jerez et al. (2013b)
	3	–	–	0.02	0.01	–	8.20 ± 0.5	35.7 ± 3	0.46 ± 0.03	AP[g]	1989	Szefer et al. (1993)
	1[i]	–	–	0.5 ± 0.12	<0.60	–	5.60 ± 0.31	24 ± 0.24	1.4 ± 0.13	Livingston is.[c]	2002–2006	Metcheva et al. (2010)

A. forsteri	4	–	–	0.35 ± 0.09	–	–	5.50 ± 2	–	–	Weddell Sea[h]	1982–1983	Steinhagen-Schneider (1986)

n/*i* not informed
[a]Sample collection
[e]Juvenile
[i]Duplicates were performed from the sample
[b]Victoria Land (East Antarctica)
[c]South Shetland Islands (West Antarctica)
[d]Antarctic Peninsula
[f]King George Island (South Shetland Islands, West Antarctica)
[g]Antarctic Peninsula (locations not specified)
[h]Northeast of the Antarctic Peninsula

Table 7 Mean trace metal levels (μg/g, dw) in stomach contents of different penguin species

Species	*N*	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
P. adeliae	5	–	–	–	–	0.08 ± 0.01	–	–	–	Terra Nova Bay[b]	1989–1990	Bargagli et al. (1998)
	1	349.72	0.47	0.45	0.07	–	4.85	26.57	6.64	King George is.[c]	2007–2010	Jerez et al. (2013a)
	2	46.80 ± 54.31	3.22 ± 0.06	1.10 ± 0.8	0.28 ± 0.19	–	66.42 ± 34.43	38.99 ± 14.05	2.20 ± 0.11	Avian is.[d]	2007–2010	Jerez et al. (2013a)
	5	282.01 ± 235.63	2.00 ± 1.58	0.23 ± 0.17	0.40 ± 0.26	–	57.81 ± 35.82	71.16 ± 48.82	10.57 ± 8.76	King George is.[c]	2008–2009	Jerez et al. (2013b)
	45	–	–	2.90	0.20	0.10	–	–	–	Edmonson Point[b]	1995	Ancora et al. (2002)
P. antarctica	2	641.07 ± 255.18	1.44 ± 1.83	0.17 ± 0.06	0.03 ± 0.04	–	51.07 ± 49.14	49.39 ± 8.3	9.33 ± 4.97	King George is.[c]	2007–2010	Jerez et al. (2013a)
	1	193.52	1.77	0.71	0.12	–	54.86	46.67	5.99	Deception is.[c]	2007–2010	Jerez et al. (2013a)
	5	477.85 ± 192.75	1.92 ± 1.11	0.32 ± 0.34	0.33 ± 0.11	–	65.67 ± 50.01	31.04 ± 10.02	12.4 ± 6.46	Deception is.[c]	2008–2009	Jerez et al. (2013b)
P. papua	2	2594.6 ± 1306.7	2.0 ± 0.09	0.09 ± 0.11	0.71 ± 0.42	–	30.51 ± 35.73	19.84 ± 4.63	82.43 ± 27.49	King George is.[c]	2007–2010	Jerez et al. (2013a)
	4[e]	854.88 ± 1000.14	0.28 ± 0.07	0.12 ± 0.07	0.05 ± 0.02	–	7.33 ± 1.13	41.09 ± 16.40	16.27 ± 15.69	King George is.[c]	2007–2010	Jerez et al. (2013a)
	5	2010.1 ± 3231.8	2.04 ± 2.92	0.24 ± 0.15	0.17 ± 0.14	–	58.69 ± 28.48	31.46 ± 12.52	36.89 ± 66.39	King George is.[c]	2008–2009	Jerez et al. (2013b)

[a]Sample collection
[b]Victoria Land (East Antarctica)
[c]South Shetland Islands (West Antarctica)
[d]Southern of the Antarctic Peninsula
[e]Juvenile

Table 8 Mean trace metal levels (μg/g, dw) in excreta of different penguin species

Species	*N*	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
P. adeliae	7	–	–	–	–	0.17 ± 0.1	–	–	–	Terra Nova Bay[b]	1989–1990	Bargagli et al. (1998)
	14	–	–	5.5	0.30	0.20	–	–	–	Edmonson Point[b]	1995	Ancora et al. (2002)
	n/i	–	–	–	0.5–3.7	0.15–0.25	–	–	–	Zhongshan Station[c]	2001	Yin et al. (2008)
	27	–	1.14 ± 0.39	3.96 ± 2.36	1.96 ± 0.86	0.52 ± 0.31	558.9 ± 217.73	262.7 ± 91.89	–	Arctowski[d]	2012–2013	Celis et al. (2015a)
	18	–	0.95 ± 0.41	2.77 ± 0.92	1.53 ± 0.75	0.40 ± 0.18	585.8 ± 196.22	215.8 ± 42.47	–	Kopaitic Island[e]	2012–2013	Celis et al. (2015a)
	10	–	0.72 ± 0.47	1.78 ± 0.39	0.59 ± 0.5	0.10 ± 0.08	402.9 ± 54.76	215.7 ± 91.18	–	Yalour is.[e]	2012–2013	Celis et al. (2015a)
	10	–	0.66 ± 0.53	1.63 ± 0.43	0.45 ± 0.39	0.13 ± 0.08	362.9 ± 38	188.4 ± 41.82	–	Avian is.[e]	2012–2013	Celis et al. (2015a)
P. antarctica	3	–	–	0.16 ± 0.01	3.80 ± 0.2	–	37.6 ± 2.0	456.0 ± 4.0	138 ± 8	AP[f]	1989	Szefer et al. (1993)
	n/i	–	–	–	1.0–1.8	0.06–0.15	–	–	–	Barton Peninsula[d]	2000	Yin et al. (2008)
	4	–	0.43 ± 0.24	3.30 ± 0.18	1.06 ± 0.6	–	168.9 ± 40.8	295.7 ± 59.01	–	Hydrurga Rocks[e]	2011–2012	Espejo et al. (2014)
	10	–	0.40 ± 0.15	1.89 ± 0.35	1.07 ± 1.5	–	229.9 ± 39.23	246.8 ± 53.37	–	Cape Shirreff[d]	2011–2012	Espejo et al. (2014)
	9	–	0.70 ± 0.26	3.13 ± 0.59	1.31 ± 0.78	–	259.99 ± 79.51	227.8 ± 63.9	–	Narebski Point[d]	2011–2012	Espejo et al. (2014)
	9	–	0.55 ± 0.31	1.88 ± 0.65	1.27 ± 0.35	–	286.7 ± 85.75	210.0 ± 115.58	–	Kopaitic Island[e]	2011–2012	Espejo et al. (2014)
P. papua	n/i	–	–	–	0.11	0.15	–	–	–	Fildes Peninsula[d]	2002	Yin et al. (2008)
	10	316 ± 47.5	5.13 ± 1.79	1.03 ± 0.36	<0.4	–	104.0 ± 2.1	145.0 ± 2.9	12.3 ± 1.2	Livingston is.[d]	2006–2007	Metcheva et al. (2011)
	10	–	0.33 ± 0.22	2.51 ± 0.89	2.89 ± 1.07	–	199.95 ± 62.47	379.99 ± 82.73	–	Base O'Higgins[e]	2011–2012	Espejo et al. (2014)
	4	–	0.44 ± 0.38	2.15 ± 0.47	0.78 ± 0.22	–	114.7 ± 41.55	192.2 ± 39.32	–	Yankee Harbor[d]	2011–2012	Espejo et al. (2014)

(continued)

Table 8 (continued)

Species	*N*	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
	3	–	0.37 ± 0.28	3.35 ± 0.23	2.55 ± 1.02	–	184.5 ± 10.81	324.3 ± 106.51	–	Mikkelsen Harbor[e]	2011–2012	Espejo et al. (2014)
	4	–	0.43 ± 0.13	2.16 ± 0.35	0.87 ± 0.53	–	130.05 ± 20.02	195.38 ± 32.84	–	Danco is.[e]	2011–2012	Espejo et al. (2014)
	10	–	0.36 ± 0.29	2.14 ± 0.91	2.74 ± 1.3	–	222.51 ± 85.48	201.2 ± 63.39	–	Base G. Videla[e]	2011–2012	Espejo et al. (2014)
	5	–	0.52 ± 0.16	2.40 ± 0.83	2.05 ± 1.95	–	154.2 ± 28.41	172.92 ± 62.85	–	Yelcho Station[e]	2011–2012	Espejo et al. (2014)
	4	–	0.33 ± 0.17	1.98 ± 0.11	2.51 ± 0.84	–	148.8 ± 32.3	246.95 ± 30.37	–	Brown Station[e]	2011–2012	Espejo et al. (2014)
	10	–	0.15 ± 0.097	0.73 ± 0.27	0.74 ± 0.953	6.60 ± 4.153	–	–	–	O'Higgins Base[e]	2011	Celis et al. (2012)
	10	–	0.38 ± 0.176	1.72 ± 0.832	0.34 ± 0.388	1.15 ± 0.828	–	–	–	Base G. Videla[e]	2011	Celis et al. (2012)
	11	–	–	1.58 ± 1.11	0.08 ± 0.08	–	146.0 ± 76.17	142.97 ± 35.51	22.43 ± 8.57	Neko Harbor[b]	2014	Celis et al. (2015b)
	10	–	–	1.24 ± 0.25	0.09 ± 0.1	–	201.5 ± 64.14	108.74 ± 25.23	17.84 ± 13.22	Doumer is.[e]	2014	Celis et al. (2015b)
	10	–	–	1.97 ± 0.86	1.46 ± 0.49	–	222.51 ± 85.48	201.2 ± 63.39	36.62 ± 16.97	Stranger Point[d]	2014	Celis et al. (2015b)
	10	–	–	2.92 ± 0.81	1.68 ± 0.58	–	266.83 ± 42.77	317.92 ± 46.6	44.75 ± 10.67	Base O'Higgins[e]	2014	Celis et al. (2015b)
S. humboldti	20	–	1.84 ± 2.65	47.7 ± 38.71	1.80 ± 0.3	0.77 ± 0.83	147.79 ± 146.42	487.11 ± 395.15	–	Pan de Azúcar is.[g]	2011–2012	Celis et al. (2014)
	19	–	0.36 ± 0.4	21.24 ± 18.35	1.59 ± 2.12	0.46 ± 0.19	69.62 ± 24.98	222.55 ± 59.2	–	Chañaral Island[g]	2011–2012	Celis et al. (2014)
	24	–	7.86 ± 4.88	42.47 ± 45.55	12.79 ± 9.97	0.61 ± 0.4	199.67 ± 81.78	0.83 ± 0.33	–	Cachagua Island[g]	2011–2012	Celis et al. (2014)
A. forsteri	5	–	–	–	–	0.31 ± 0.03	–	–	–	Terra Nova Bay[b]	1989–1990	Bargagli et al. (1998)
A. patagonicus	n/i	–	–	–	0.6–1.1	0.25–0.35	–	–	–	Zhongshan Station[c]	2001	Yin et al. (2008)

n/*i* not informed
[a]Sample collection

(continued)

[b]Victoria Land (East Antarctica)
[c]Mirror Peninsula (East Antarctica)
[d]South Shetland Islands (West Antarctica)
[e]Antarctic Peninsula (West Antarctica)
[f]Antarctic Peninsula (locations not specified)
[g]Coast of Chile

Table 9 Mean trace metal levels (μg/g, dry weight) in blood, brain, testicles, embryo, spleen, and heart of different penguin species

Matrix	*N*	Species	Al	As	Cd	Pb	Hg	Cu	Zn	Mn	Locations	Date[a]	References
Blood	10	*E. minor*	3.89 ± 1.26	3.72 ± 1.76	–	0.07 ± 0.02	2.75 ± 0.85	2.48 ± 0.44	37.97 ± 5.28	–	St. Kilda[b]	2012	Finger et al. (2015)
Blood	11	*E. minor*	3.19 ± 0.84	1.07 ± 1.22	–	0.04 ± 0.01	0.86 ± 0.23	2.14 ± 0.42	33.47 ± 3.27	–	Phillip is.[b]	2012	Finger et al. (2015)
Blood	10	*E. minor*	4.22 ± 1.67	0.67 ± 0.43	–	0.04 ± 0.01	0.84 ± 0.37	2.32 ± 0.40	38.77 ± 6.76	–	Notch is.[b]	2012	Finger et al. (2015)
Brain	1	*P. adeliae*	–	–	–	–	0.43	–	–	–	Terra Nova Bay[c]	1989–1990	Bargagli et al. (1998)
Testicles	1	*P. adeliae*	–	–	–	–	0.42	–	–	–	Terra Nova Bay[c]	1989–1990	Bargagli et al. (1998)
Embryo	12	*P. papua*	14.56 ± 2.4	<0.3	<0.05	<0.4	–	2.82 ± 0.7	25.27 ± 2.5	0.67 ± 0.06	Livingston is.[d]	2006–2007	Metcheva et al. (2011)
Spleen	1[e]	*P. papua*	–	–	3.5 ± 0.41	< 0.95	–	24.7 ± 0.19	232.0 ± 2.67	6.30 ± 0.15	Livingston is.[d]	2002–2006	Metcheva et al. (2010)
Heart	1[e]	*P. papua*	–	–	0.1 ± 0.02	0.20 ± 0.09	–	11.3 ± 0.09	91.5 ± 0.67	1.0 ± 0.25	Livingston is.[d]	2002–2006	Metcheva et al. (2010)

[a]Sample collection
[b]Victoria (Australia)
[c]Victoria Land (East Antarctica)
[d]South Shetland Islands (West Antarctica)
[e]Duplicates were performed from the sample

feathers of pygoscelid penguins from Antarctica. Metals such as Mo, V, or Y have not been reported in penguins.

Feathers constitute the most common biological matrix used in situ for determining trace elements in penguins (Table 1). Metals are delivered mainly by the blood supply, which is linked to the feeding habits of the bird (Metcheva et al. 2006). Some evidence shows that the concentration of Hg in feathers reflects levels in the blood during formation (Dauwe et al. 2005). Trace element burdens in feathers express past exposure and accumulation during the inter-moult period, thus they are more representative of long-term rather than acute exposure, at least for Hg (Furness et al. 1986). Reports in penguin feathers comprise ten species, most of which are from Antarctica and subantarctic islands (Table 1). Similarly, there is plenty of information of trace elements in penguin guano, particularly from Antarctica (Table 8), but there are few data on other species that live in lower latitudes, except for a study of Humboldt penguins (*Spheniscus humboldti*) from the coast of Chile (Celis et al. 2014).

There is very little information on trace elements in penguin eggshells (Table 2), bones (Table 3), and kidneys (Table 4). Concentrations of trace elements in blood, brain, testicles, embryo, spleen, and heart of penguins have been poorly investigated (Table 9). Studies of trace elements in the liver of penguins (Table 5) correspond mostly to species that inhabit the Antarctica and subantarctic islands. Data of trace elements in muscles of penguins are scarce and they are exclusively focused on species that inhabit Antarctica (Table 6). Studies on metals in stomach contents of penguins are scarce and all of them have been carried out in Antarctica (Table 7).

Trace elements are chemicals that occur in natural and perturbed environments in small amounts (Prashanth et al. 2016). Their inadequate intake can damage the function of cells, causing physiological disorders and disease (Soria et al. 1995). These chemicals can be classified according to their biological significance, as non-essential and essential trace elements. Non-essential elements, such as Pb, Be, Cd, Hg, As, Sb, and Ti, have no known function in the animal body, and their presence may produce toxicity. Essential elements (Cr, Co, Cr, Cu, Fe, Mo, Se, Zn, and Mn) are required in small amounts because they perform vital functions for the maintenance of animal life, growth, and reproduction (Nordberg and Nordberg 2016). Some trace elements such as Ni, Sn, V, and Al cannot be yet classified as essential, as their role is not clear in animals, including humans (Prashanth et al. 2016). In general, the information available on concentrations of trace elements is fragmented in time and space, so it is not possible to build trends. Therefore, implementations of monitoring programs that incorporate these variables are required.

3.1 Non-essential Trace Elements

3.1.1 Aluminum

The maximum concentrations of Al have been found in stomach contents of gentoo penguins from King George Island, Antarctica (2595 μg/g, Table 7) and in feathers of adult chinstrap penguins from Deception Island, Antarctica (203.13 μg/g, Table 1). In contrast, the lowest concentration of Al (0.55 μg/g) has been reported in livers of Adélie penguins from Avian Island, Antarctica (Table 5). The high Al levels found in penguins from King George and Deception Islands could be linked to the abundance of this metal in bioavailable forms in the sediments of these areas (dos Santos et al. 2005; Deheyn et al. 2005).

Concentrations of Al in penguin feathers (0.71–203.13 μg/g) are highest in adult chinstrap penguins at Deception Island, whereas the lowest concentrations are in juvenile Adélie penguins at Avian Island (Table 1). This range is lower than the concentrations of Al (96–866 μg/g) in feathers of birds from Europe and North America (Rattner et al. 2008; Lucia et al. 2010). Highest concentrations of Al (866 μg/g) have been measured in feathers of osprey eagles (*Pandion haliaetus*) (Rattner et al. 2008).

Only one study reports the concentration of Al in penguin eggshells (28.96 μg/g, Table 2), which is higher than that found by Custer et al. (2007) in seagulls of North America (3.3 μg/g).

Concentrations of Al in penguin bones (4.16–69.95 μg/g) are the highest in gentoo penguins from King George Island, while the lowest concentrations are in chinstrap penguins from the same location (Table 3). Studies on levels of Al in bones of seabirds are scarce, and the few data in penguins are all from species from genera *Pygoscelis* and *Aptenodytes*, being higher than those of birds from the Northern Hemisphere (1.37–6.9 μg/g, Dauwe et al. 2005).

In kidneys, Al concentrations (0.69–14.12 μg/g, Table 4) are highest in Adélie penguins from Avian Island and are lowest in chinstrap penguins from King George Island. In comparison, Al levels in kidneys of aquatic birds from the Southwest coast of France (6.1–8.9 μg/g, Lucia et al. 2010) are within the range reported in the penguin kidneys from Antarctica.

Concentrations of Al in the liver (0.55–15.52 μg/g, Table 5) are highest in chinstrap penguins from Deception Island (Table 5), whereas the lowest concentrations of Al correspond to Adélie penguins from Avian Island. There is little information about the levels of Al in livers of seabirds, although it is possible to see that the concentrations of Al in penguins are within the range reported in the aquatic and terrestrial birds from Europe (0.18–37.3 μg/g) (Scheuhammer 1987; Dauwe et al. 2005).

In muscles, Al concentrations (1.07–114.88 μg/g, Table 6) are highest in chinstrap penguins from Deception Island, whereas the lowest concentrations are in the same species from King George Island. Despite the lack of data on seabirds from other regions, levels of Al in penguin muscles are higher than those found in a study carried out from Europe in muscles of the Great tit (0.08–1.46 μg/g, Dauwe et al. 2005).

Concentrations of Al in penguin stomachs (46.80–2594.6 μg/g, Table 7) are highest in gentoo penguins from King George Island, whereas the lowest concentrations are in Adélie penguins from Avian Island. This range is higher than the concentrations of Al (0.22–23.5 μg/g) in stomach contents of wild birds from Europe (Dauwe et al. 2005).

There is only one measurement of Al in excreta (316 μg/g, Table 8), which is from gentoo penguins at Livingston Island, showing a deficit of information for this element. No Al was found in guano of other seabirds. Birds are most likely exposed to Al through their diets, and most Al is excreted via the feces and only a fraction is retained (Sparling and Lowe 1996).

In blood, the only existing study corresponds to the little penguin (*Eudyptula minor*), and Al concentrations (3.19–4.22 μg/g, Table 9) present less variability and are within the range reported in the seagulls of the Northern Hemisphere (1.34–4.11 μg/g, Kim et al. 2013).

The main toxic effects of Al that have been reported in animals are produced in the central nervous system, though long-lasting exposures can also affect the skeletal system, decreasing its rate of formation and increasing the risk of fractures. The functioning of the renal, endocrine, reproductive, and cardiac systems is also affected by a chronic exposure to this metal (Sjögren et al. 2007). In birds, Al is poorly absorbed and its potential for toxicity is low, thus Al levels in soft tissue do not necessarily reflect toxicity to the individual (Scheuhammer 1987). Nevertheless, there is some evidence indicating that Al found in the bone marrow tissue of humeri of wild pied flycatchers (*Ficedula hypoleuca*) can produce small clutches, defective eggshell formation, and intrauterine bleeding, similar to the symptoms of Al intoxication in mammals (Nyholm 1981). Al interferes with the deposition of Ca, resulting in weak bones and eggs, besides affecting the reproductive capacity (Nayak 2002). No studies have been performed in penguins to determine any possible effects produced by this metal.

3.1.2 Arsenic

The maximum As concentrations in tissues and organs are in the liver of Adélie penguins (*Pygoscelis adeliae*) from King George Island (1.2 μg/g, Table 5) and kidneys of the same species and location (1.07 μg/g, Table 4). In contrast, the lowest concentration of As (0.01 μg/g) has been reported in feathers of adult chinstrap penguins (*Pygoscelis antarctica*) from Livingston Island, Antarctica (Table 1). Arsenic tends to accumulate in almost all organs, mainly in the liver where biomethylation of As takes place producing some kind of acids, such as monomethylarsonic and dimethylarsonic (Khan et al. 2014).

Concentrations of As in feathers (0.01–0.88 μg/g, Table 1) are highest in adult gentoo penguins that inhabit Livingston Island, and are lowest in adult chinstrap penguins from Livingston Island. Arsenic concentrations in feathers of black-legged kittiwakes (*Rissa tridactyla*) and black oystercatchers (*Haematopus bachmani*) from Alaska (0.17–0.34 μg/g, Burger et al. 2008) and in feathers of black-tailed gull chicks (*Larus crassirostris*) from Korea (0.15–0.44 μg/g, Kim et al. 2013) are within the range found in the penguins. There is little information on the levels of As in penguin eggshells (Table 2).

In bones, concentrations of As are highest in gentoo penguins that inhabit Byers Peninsula (Table 3), while the lowest concentrations are in chinstrap penguins from Deception Island. Concentrations of As in penguin bones (0.04–0.19 μg/g) are within the range reported in the aquatic and terrestrial birds of the Northern Hemisphere (<0.0001–1.60 μg/g, Lebedeva 1997).

In kidneys, As concentrations (0.38–1.07 μg/g, Table 4) are highest in Adélie penguins from King George Island and lowest in the same species from Avian island. Arsenic levels in penguin kidneys are within the range found in the kidneys of passerine birds from the Northern Hemisphere (0.071–1.81 μg/g, Sánchez-Virosta et al. 2015).

In the liver, the content of As (0.30–1.20 μg/g) is highest in adult Adélie penguins from King George Island, and the lowest in juvenile same species, location, and sampling date (Table 5). The highest levels of As in adult penguins is probably due to the fact that this element accumulates in the animal body, and thus its level is directly related to the age of the individuals (Khan et al. 2014). The concentrations of As in penguin livers are lower than those found in seabirds of the Northern Hemisphere (0.22–5.62 μg/g) (Lucia et al. 2010; Ribeiro et al. 2009; Skoric et al. 2012).

In muscles, As concentrations (0.18–1.04 μg/g, Table 6) are highest in chinstrap penguins from Deception Island, and lowest in Adélie penguins from King George Island. The concentrations of As in penguin muscles are higher than those reported in wild birds from the Northern Hemisphere (0.01–0.35 μg/g, Gasparik et al. 2010).

In the stomach, As concentrations are highest in Adélie penguins from Avian Island, and are lowest in the same species from King George Island (Table 7). Arsenic concentrations in penguin stomach contents (0.28–3.22 μg/g) are higher than those levels found in wild birds from Europe (0.006–0.76 μg/g, Dauwe et al. 2005).

In excreta, As concentrations are highest in Humboldt penguins from Cachagua Island (Chile), and lowest in gentoo penguins from O'Higgins Base, Antarctic Peninsula (Table 8). In general, levels of As in penguin guano (0.15–7.86 μg/g) are lower than those levels found in guano of wild birds from the Northern Hemisphere (0.42–16.03 μg/g, Dauwe et al. 2000; Kler et al. 2014).

In blood, the highest As concentration is in the little penguin from Australia (Table 9). Levels of As in penguin blood (0.67–3.72 μg/g) are higher than those levels observed in black-tailed gull chicks of the Northern Hemisphere (0.26–0.48 μg/g, Kim et al. 2013).

Generally, in birds As is initially accumulated in liver and kidneys and subsequently it is redistributed to feathers and claws (Sánchez-Virosta et al. 2015). To counter the effects of exposure to As, organisms have biotransformation mechanisms that decrease its toxicity, in which inactive As metabolites are formed (monomethylarsenic and dimethylarsenic), which are more easily removed by the kidneys (Soria et al. 1995; ATSDR 2007). In ducklings, clinico-pathological effects caused by sodium arsenate at 30–300 μg/g can produce liver congestion, necrosis and fibrosis, severe degeneration of brain, and increase mortality (Khan et al. 2014).

In general, the levels of As reported in feathers, blood, and organs of penguins are below 3 μg/g, the limit considered normal in living organisms (Jerez et al. 2013a), except for the concentrations of As in blood of little penguins that inhabit St Kilda, on the coast of Australia (3.72 μg/g, Table 6). All the studies performed in penguins reveal that the concentrations of As are below 50 μg/g known as of toxicological significance, or that can lead to endocrine disorders (Neff 1997).

3.1.3 Cadmium

This metal is known to bioaccumulate in marine biota from both natural and anthropogenic sources (Espejo et al. 2014). The maximum concentrations of Cd (351.8 μg/g) have been found in kidneys of Adélie penguins from Avian Island, Antarctic Peninsula (Table 4). In contrast, the lowest concentration of Cd (<0.001 μg/g) has been reported in bones (Table 3) and muscles (Table 6) of chinstrap penguins and Adélie penguins from Antarctica, respectively. In general, birds accumulate Cd in their bodies through the food chain, and Cd is first accumulated in the liver and then transported to several organs (Lee 1996). Cadmium concentrations in penguins tended to be higher in kidneys than in the liver, as also noted in different species of Anseriformes (Jin et al. 2012).

In feathers, the maximum Cd concentrations have been found in adult gentoo penguins from Livingston Island, and the minimum in juvenile Adélie penguins from King George Island (0.01–0.50 μg/g, Table 1). In general, Cd concentrations in penguin feathers are lower than those found in seabirds of the Northern Hemisphere (0.04–1.28 μg/g) (Kim et al. 1998; Agusa et al. 2005; Mansouri et al. 2012). In eggshells, there is little information on the levels of Cd in penguins (Table 2).

In bones, Cd concentrations (<0.001–0.17 μg/g, Table 3) are maximum in Adélie penguins from Avian Island, and minimum in chinstrap penguins from King George Island. The concentrations of Cd in penguin bones are lower than those reported in bones of seabirds of the Northern Hemisphere (0.03–0.33 μg/g, Kim et al. 1998).

In kidneys, Cd concentrations (0.2–351.8 μg/g, Table 4) are highest in Adélie penguins from Avian Island, and are lowest in gentoo and Adélie penguins, both from King George Island. Cadmium levels in kidneys of gulls (0.90–44.4 μg/g) of south-western Poland and the Artic (Orłowski et al. 2007; Malinga et al. 2010) are within the range reported in penguin kidneys. A study found that Cd levels in kidneys of scoters (*Melanitta perspicillata*) from the Queen Charlotte Islands in Canada were as high as 390.2 μg/g, a concentration potentially associated with renal damage (Barjaktarovic et al. 2002).

In the liver, Cd concentrations (0.06–27.7 μg/g, Table 5) are highest in Emperor penguins from the Weddell Sea, and are lowest in Adélie penguins from King

George Island. Cadmium concentrations in penguin livers reveal that 9 of 19 reports (47.4%) exceeded the threshold levels of toxicity for wild birds (3 μg/g, Scheuhammer 1987). The Cd levels in penguin livers are comparable with those levels (0.05–15.1 μg/g) found in seabirds of the Northern Hemisphere (Elliot et al. 1992; Kim and Koo 2007; Pérez-López et al. 2005).

In muscles, Cd levels of seabirds (0.26–0.52 μg/g) from the Northern Hemisphere (Orłowski et al. 2007; Malinga et al. 2010) are within the range reported in penguins (<0.001–2.63 μg/g, Table 6). The highest Cd levels are in Adélie penguins from Avian Island, and are lowest in the same species from Potter Cove.

In the stomach, Cd concentrations (0.09–2.9 μg/g, Table 7) are highest in Adélie penguins from Edmonson Point, and are lowest in gentoo penguins from King George Island. The levels of Cd in penguin stomach contents are far below those levels of Cd detected in the stomach contents of seabirds from industrialized areas of Korea (96–217 μg/g) (Kim and Oh 2014b, c).

In excreta, Cd levels are linked to high dietary Cd intake (Ancora et al. 2002). Cd concentrations (0.16–47.7 μg/g, Table 8) are highest in Humboldt penguins from Pan de Azúcar Island (Chile), and are lowest in Adélie penguins from the Antarctic Peninsula. Levels of Cd in penguin excreta are higher than those observed in wild bird species (0.12–1.88 μg/g) of the Northern Hemisphere (Kaur and Dhanju 2013; Kler et al. 2014).

In birds, the accumulation of Cd can have adverse effects on health, such as renal and testicular damage, disorder in the balance of Ca and the skeletal integrity, reduced feed intake and growth rate, decreased egg laying, thinning eggshells, or alteration in the behavior of the bird, among other effects (Burger 2008; Furness 1996; Larison et al. 2000; Rodrigue et al. 2007). However, seabirds seem to be less vulnerable to the exposure to high levels of Cd than other wild organisms and birds of terrestrial environments (Burger 2008; Furness 1996). Highest Cd concentrations in tissues of marine birds were in kidney tissue of oceanic birds (Elliot et al. 1992; Pérez-López et al. 2005; Orłowski et al. 2007; Kim and Koo 2007; Malinga et al. 2010). In *Pygoscelis* penguins from the South Shetland Islands, a ratio kidney/liver for Cd concentrations of about 4 means a higher Cd affinity for renal tissue (Jerez et al. 2013b), thus indicating a chronic or sub-chronic exposure to Cd due to maternal transfer of this metal during egg development, as occurs in other seabirds (Agusa et al. 2005). A high exposure to Cd causes significant accumulation of this metal in the soft tissues, because a small proportion is excreted, and release of Cd from kidney is very slow (Eisler 1985). Thus, under conditions of chronic dietary exposure, kidney concentrations of Cd may express long-term accumulation (Scheuhammer 1987).

Toxic effects of Cd appear in humans and other mammals when kidney Cd levels reach about 100 μg/g ww (Scheuhammer 1987) or about 400 μg/g dw (assuming a moisture content of 75% in the sample). Seabirds accumulate a large amount of metals such as Hg in their liver because they usually occupy the highest trophic positions in the marine food web and have a long life span (Thompson 1990). However, birds are relatively resistant to some metals, like Cu (Eisler 1998). The process of the metal detoxification in livers of seabirds is well described by Ikemoto et al. (2004). In penguins, some metals interact with others to activate certain phase I detoxification mechanisms in the organism. A study carried out by Kehrig et al. (2015) evidenced a correlation between Se and metallothioneins in liver samples of Magellanic penguins (*Spheniscus magellanicus*), indicating that Se would be involved in detoxification of Cd, Pb, and Hg. Another study showed a positive correlation between Se and Cd in tissues of chinstrap, gentoo, and Adélie penguins, which would be related to the detoxifying function played by Se against the toxicity of Cd (Jerez et al. 2011). In this sense, Jerez et al. (2013a) stated that high levels of Se (30.6 μg/g) and Zn (126.05 μg/g) can protect chinstrap penguins of Deception Island at least partially against high Cd levels (27.54 μg/g) of toxicological significance. However, the accumulation of Cd and Se, and likely other heavy metals, can cause teratogenic effects in a wide range of birds and animal species (Hoffman 2002; Gilani and Alibhai 1990; Ohlendorf et al. 1988; Franson et al. 2007), and even micromelia in penguins (Raidal et al. 2006). High Se levels of over 10 μg/g in liver of aquatic birds can produce hepatic toxicity (Lemley 1993). A study found that 47% of the samples of livers of penguins from Antarctic Peninsula had Se levels above the mentioned toxicity threshold (Jerez et al. 2013a). However, when evaluating Se toxicity and oxidative stress, nutritional factors should be taken into consideration (Franson et al. 2007).

Studies carried out in colonies of some penguins from Antarctica have shown that kidney samples collected at Weddell sea and Avian Island present high concentrations of Cd (270.2 and 351.8 μg/g, Table 4), implying that those seabirds probably presented a chronic exposure to this metal, with levels above the toxicity threshold established for birds (Furness 1996).

3.1.4 Mercury

The maximum concentrations of Hg (8.16 μg/g, Table 1) have been found in feathers of adult gentoo penguins from Crozet Islands. In contrast, the lowest concentration of Hg (0.005 μg/g) has been reported in eggshells of Adélie penguins from Admiralty Bay, Antarctica (Table 2). As with most seabirds, penguin feathers constitute an important way of detoxification of Hg (Yin et al. 2008).

In feathers, Hg concentrations (0.033–8.16 μg/g, Table 1) are highest in adult gentoo penguins from Crozet Islands (Carravieri et al. 2016). The lowest Hg levels have been reported in juvenile Magellanic penguins from the coasts of Argentina (Frias et al. 2012). Mercury concentrations in penguin feathers are lower than those found in different species of seagulls and terns from Northern Hemisphere (0.31–20.2 μg/g) (Goutner et al. 2000; Zamani-Ahmadmahmoodi et al. 2014) and in feathers of birds from various locations of the Chilean coast (0.11–13 μg/g, Ochoa-Acuña et al. 2002). Of the thirty-two reports in penguin feathers, only two studies are in the range of Hg levels (5–40 μg/g) linked to reduced hatched of egg laid in various bird species (Eisler 1987). Concentrations of Hg of 9–20 μg/g in feathers can decrease reproductive success in some piscivorous birds (Fimreite

1974; Scheuhammer 1987; Beyer et al. 1997; Evers et al. 2008). The range of Hg concentrations reported in penguin feathers are below those known to cause adverse health and reproductive effects in birds.

In eggshells, Hg concentrations (0.005–0.26 μg/g, Table 2) are highest in Adélie penguins from Terra Nova Bay (Bargagli et al. 1998), and are lowest in the same species in Almiralty Bay (Santos et al. 2006). Mercury levels in penguin eggshells are lower than those reported in marine, aquatic, and terrestrial birds of other latitudes (0.05–36.37 μg/g) (Yin et al. 2008; Daso et al. 2015).

In bones, a single study reported Hg concentrations (0.02 μg/g, Table 3) in Adélie penguins that inhabit the surroundings of the Zhongshan Station (Yin et al. 2008). In general, data of Hg in bones of birds are not abundant, because this metal is not precisely stored in this biotic matrix, making comparisons difficult. In any case, levels of Hg in penguin bones are 50% lower than those detected in bones of seagulls from the coasts of Japan (Agusa et al. 2005) and much lower than those in great cormorants (*Phalacrocorax carbo*) from Europe (1.4–1.72 μg/g, Skoric et al. 2012).

In kidneys, Hg concentrations (0.146–2.47 μg/g, Table 4) are highest in Magellanic penguins from the coast of Southern Brazil (Kehrig et al. 2015). The lowest levels are reported in Adélie penguins that inhabit King George Island (Smichowski et al. 2006). Mercury concentrations in penguin kidneys are lower than those detected in kidneys of seabirds from the Northern Hemisphere (0.3–5 μg/g) (Arcos et al. 2002; Zamani-Ahmadmahmoodi et al. 2014).

In livers, Hg concentrations (0.269–5.7 μg/g, Table 5) are highest in Magellanic penguins from the coasts of Southern Brazil (Kehrig et al. 2015). The lowest concentrations of Hg have been reported in Adélie penguins from Potter Cove, King George Island (Smichowski et al. 2006). Mercury concentrations in penguin livers are below those reported in seabirds of the Northern Hemisphere (4.9–306 μg/g, Kim et al. 1996). In birds, sublethal effects of Hg on growth, development, reproduction, blood and tissue chemistry, metabolism, behavior, histopathology, and bioaccumulation have been found between 4 and 40 mg/kg (dietary intake) (Eisler 1987). The concentrations of Hg in liver of Magellanic penguins from Rio Grande do Sul, Brazil (5.7 μg/g, Table 5) are higher than the threshold of toxicity for Hg (Kehrig et al. 2015).

In muscles, Hg is reported by a single study in Adélie penguins (0.6 μg/g, Table 6) from Terra Nova Bay (Bargagli et al. 1998). Levels of Hg in penguin muscles are lower than those reported in terns and gulls from Asia (0.9–2.5 μg/g, Zamani-Ahmadmahmoodi et al. 2014).

In stomachs, Hg (0.08–0.10 μg/g, Table 7) is lowest in Adélie penguins from Terra Nova Bay (Bargagli et al. 1998) and is highest in the same species from Edmonson Point (Ancora et al. 2002). It was difficult to find more reports of Hg levels in bird stomachs. Levels of Hg detected in penguin stomachs are much lower than those measured in intestines of cormorants from Europe (1.29–2.49 μg/g, Skoric et al. 2012).

In excreta, Hg concentrations (0.06–6.60 μg/g, Table 8) are highest in gentoo penguins from O'Higgins Base, and are lowest in chinstrap penguins from Barton

Peninsula, both locations of the Antarctic Peninsula. Levels of Hg in penguin excreta are higher than those in other marine birds worldwide (0.10–0.75 μg/g, Yin et al. 2008).

Mercury concentrations in penguin blood (0.84–2.75 μg/g) and in penguin brains (0.43 μg/g) are been measured in little penguins from Australia and Adélie penguins from Terra Nova Bay (Antarctica), respectively (Table 9). Those levels are higher than those found in the blood of black-tailed gull chicks and Great tits from the Northern Hemisphere (0.03–0.26 μg/g) (Dauwe et al. 2000; Kim et al. 2013). Mercury concentrations of over 3 μg/g in blood can affect endocrine systems of Arctic birds with negative consequences for reproduction (Tartu et al. 2013). In loons (*Gavia immer*), Evers et al. (2008) reported an adverse effect threshold for adult birds at 3 μg/g (w.w) in blood and reproductive failure when adult blood Hg levels reach 12 μg/g/(w.w). Tartu et al. (2016) found that Hg levels (1.0–1.5 μg/g) in blood of adult kittiwakes can disrupt prolactin secretion (a pituitary hormone involved in parental care) which could lead to reduced chick survival.

Chronic exposure to metals may imply a threat to penguins. Some evidence shows that the survival and breeding success decreased with increasing Hg levels in blood of Artic seabird (2.28 ± 0.42 μg/g, Goutte et al. 2015). Mercury in its organic form (methylmercury, ethylmercury) is more lipophilic, which favors its accumulation mainly in the liver, kidneys, brain, and feathers. Inorganic Hg is mostly accumulated in kidneys, due to its affinity to metallothioneins presented by renal cells (Byrns and Penning 2011). In seabirds, habitat type and functional feeding group may influence organic Hg bioaccumulation rates at higher trophic levels (Chen et al. 2008). The direct effects of elevated organic Hg on marine biota can include changes in brain neurochemical receptor density (Scheuhammer et al. 2008). In pinnipeds, adverse effects may manifest as immunosuppression (Lalancette et al. 2003). There are few studies on the effects of metals in feathers and blood of birds, but evidence exits indicating that concentrations of Hg of 5 μg/g in feathers of birds can cause reproductive impairment (Burger and Gochfeld 1997), including smaller egg size, lower hatching rate, decreased chick survival, and even impaired territorial fidelity in waterfowl (Rothschild and Duffy 2005). The few studies that exist reveal that the concentrations of Hg in biotic matrices of penguins from Antarctica are below the stated threshold of toxicological significance for Hg. In general, Hg levels are lower in most of the biological matrices of penguins than birds from the Northern Hemisphere.

3.1.5 Lead

Excepting excreta, the maximum concentrations of Pb (almost 1.90 μg/g) have been found in feathers of adult gentoo penguins from Livingston Island (Table 1) and in bones of Adélie penguins from East Antarctica (1.60 μg/g, Table 3). In contrast, the lowest concentration of Pb (<0.001 μg/g) has been reported in kidneys (Table 4), liver (Table 5), and muscles (Table 6) of gentoo penguins from King George Island.

Lead is not metabolically regulated (Gochfeld et al. 1996), and unlike Cd, tends to be accumulated in bird feathers (Jerez et al. 2011).

In feathers, Pb concentrations (Table 1) are highest (almost 1.90 μg/g) in adult gentoo penguins from Livingston Island. On the other hand, Pb levels are lowest (<0.01 μg/g) in juvenile Adélie penguins from King George Island. The highest concentration of Pb in penguin feathers is directly related to major human activity (Jerez et al. 2011, 2013a). Levels of Pb in penguin feathers are lower than those concentrations found in feathers (0.34–7.15 μg/g) of different seabirds of the Northern Hemisphere (Kim et al. 1998; Burger et al. 2008; Ribeiro et al. 2009; Skoric et al. 2012; Kim and Oh 2014b). Lead concentrations of 4 μg/g (dw) in feathers are known to be a threshold level for toxicity (Burger and Gochfeld 2000b).

In eggshells, Pb levels in penguin eggshells are rare. The highest Pb concentrations (0.75 μg/g, Table 2) have been found in gentoo penguins from Fildes Peninsula (Yin et al. 2008). Levels of Pb (0.68–0.75 μg/g) in eggshells of penguins are lower than those reported in seabirds (1.25–3.10 μg/g) of the Northern Hemisphere (Yin et al. 2008; Kim and Oh 2014a).

In bones, Pb concentrations (<0.001–1.60 μg/g, Table 3) are highest in Adélie penguins from Zhongshan Station (Yin et al. 2008), and are lowest in *Pygoscelis* penguins from King George Island and Byers Peninsula (Barbosa et al. 2013; Jerez et al. 2013a). The concentrations of Pb in bones of penguins are lower than those reported in bones of marine, aquatic, and terrestrial bones (0.04–42.32 μg/g) of the Northern Hemisphere (Lebedeva 1997; Kim et al. 1998; Orłowski et al. 2007; Yin et al. 2008). Lead is known to be a toxic metal, and the skeleton is the main depot for these elements (Lebedeva 1997). Lead levels >10 μg/g in bone of wild birds are considered to be toxic, and so may be interpreted as a result of relatively polluted habitats (Scheuhammer 1987). Bone Pb concentrations higher than 20 μg/g are considered as excessive exposure for waterfowls (Franson 1996). Levels in penguin bones are far below those threshold values, which suggest that the biological effect should be neglected.

In kidneys, Pb concentrations (<0.001–0.55 μg/g, Table 4) are highest in Magellanic penguins from the coast of Southern Brazil (Kehrig et al. 2015), and are lowest in gentoo penguins from King George Island (Jerez et al. 2013b). Concentrations of Pb in penguin kidneys are lower than those of seabirds from the Northern Hemisphere (0.14–11.18 μg/g) (Kim et al. 1998; Orłowski et al. 2007). Lead concentrations above 68 μg/g in kidneys of snowy owls (*Nyctea scandiaca*) are linked to bird's mortality (Franson 1996).

In the liver, Pb levels varies from <0.001 to 0.58 μg/g (Table 5) with the highest concentrations in Magellanic penguins from the coasts of Southern Brazil (Kehrig et al. 2015). The lowest levels are reported in gentoo penguins from King George Island (Jerez et al. 2013b). Concentrations of Pb in penguin livers are lower than values (0.50–3.71 μg/g) found in seabirds of Asia (Kim et al. 1998; Kim and Koo 2007; Kim and Oh 2014c). A study conducted in South Korea (Kim and Oh 2014c) found that high levels of Pb in liver (6.2 μg/g) could negatively affect both behavior and growth of chicks of the black-tailed gull. Concentrations of Pb in livers of penguins are far below this threshold value. Hepatic Pb concentrations of over

30 μg/g in waterfowls can produce Pb poisoning, which is characterized by impaction of the upper alimentary tract, submandibular edema, myocardial necrosis, and biliary discoloration of the liver (Beyer et al. 1998).

In muscles, Pb concentrations (Table 6) are highest (almost 0.60 μg/g) in gentoo penguins from Livingston Island (Metcheva et al. 2010), and are lowest (<0.001 μg/g) in the same species of King George Island (Jerez et al. 2013b). In general, the levels of Pb in penguin muscles are lower than those reported in seabirds (0.014–3.59 μg/g) of the Northern Hemisphere (Kim et al. 1998; Orłowski et al. 2007).

In the stomach, Pb concentrations (0.03–0.71 μg/g, Table 7) are highest in gentoo penguins from King George Island, and are lowest in chinstrap penguins from King George Island. The levels of Pb in stomach contents of penguins are lower than those levels of Pb (0.059–105.0 μg/g) detected in stomach contents of seabirds from the Northern Hemisphere (Kim et al. 1998; Kim and Oh 2014b, c).

In excreta, Pb concentrations (0.08–12.79 μg/g, Table 8) are highest in Humboldt penguins from Cachagua Island (Celis et al. 2014), while the lowest levels were reported in gentoo penguins from Neko Harbor, Antarctic Peninsula (Celis et al. 2015b). In general, levels of Pb in penguin guano are lower than the concentrations of Pb (3.90–124.8 μg/g) in guano of aquatic and terrestrial birds from the Northern Hemisphere (Dauwe et al. 2000; Martinez-Haro et al. 2010; Kler et al. 2014).

In blood, Pb concentrations (0.04–0.07 μg/g, Table 9) have been measured only in little penguins from the coast of Australia. Those Pb levels are below the deleterious effect level of 4 μg/g (Finger et al. 2015), and are also lower than those reported in gulls from the Northern Hemisphere (0.06–0.18 μg/g, Kim et al. 2013). Some biological functions of birds can be altered when Pb levels in blood >3 μg/g and Pb levels >6 μg/g can produce uremic poisoning (Franson 1996).

In birds, it has been observed that the exposure to Pb in young individuals of the herring gull (*Larus argenteus*) and the common tern (*Sterna hirundo*) affects behavioral development, growth, locomotion, balance, search for food, thermoregulation, and recognition between individuals (Burger and Gochfeld 2000a). Pb is transported through blood bonded to hemoglobin, reaching the liver, kidneys, bone marrow, and central nervous system. Nevertheless, Pb can be stored in tissues rich in Ca such as hairs, feathers, and bones, where it can remain for many years (O'Flaherty 1998). Lead in penguin bones is accumulated throughout the lifetime of the individual, and so its presence in bones may be considered an indicator of long-term exposure (Barbosa et al. 2013). A study for *Pygoscelis* penguins from Antarctica found that Cd, Ni, Pb, and Se levels in muscles are long-term dependent (Jerez et al. 2013a). High concentrations of Cu might increase the effects of toxicological significance in penguins caused by Pb (Eisler 1988).

Feces can be used to detect adverse toxicological effects in wildlife by means of porphyrins, which can be correlated with metals measured in the same sample (Mateo et al. 2016). A study showed a strong affinity between the levels of Pb with porphyrins in excreta of gentoo penguins (Celis et al. 2012), which may be associated with hepatic and renal damage (Casini et al. 2003). Available data indicate that concentrations of Pb in guano of penguins in the Antarctica have increased in the last 200 years as a result of greater local anthropogenic activity (Sun and Xie 2001). Studies that are able to show the possible biological effects of Pb on these populations of polar seabirds are needed.

Negative correlations between Pb–Cu and Pb–Fe have been found in livers of *Pygoscelis* penguins (Jerez et al. 2013a), indicating the capability of Pb (a metal directly linked to various anthropogenic activities) to use the transport mechanisms of the essential cations, preventing them from performing their metabolic function (Ballatori 2002). Penguin species from higher latitudes could be more vulnerable to the effects of trace elements due to their less effective immunological systems in such environments in comparison to other species of penguins that live in lower latitudes (Boersma 2008; Cooper et al. 2009).

There are few studies on the exposure to heavy metals in penguins and it is necessary to progress in the use of non-destructive biomarkers and non-invasive matrices (i.e., feathers or fecal material) or semi-invasive such as blood tissue. Porphyrins have proved to be useful biomarkers of exposure to contaminants (Casini et al. 2003), because they are capable of bonding to metals and they can be detected in different biological matrices (De Matteis and Lim 1994). Some trace metals can interfere with the biosynthesis of hemoglobin and cause alterations in the porphyrins, which are accumulated or excreted (Casini et al. 2001). Byproducts such as copro- uro- and protoporphyrins are not toxic in normal concentrations, but when there is an excess they can affect the liver and bone marrow (Lim 1991). A study showed a positive correlation between the levels of porphyrins and those of Hg and Pb in guano of gentoo penguins (Celis et al. 2012). Another study carried out in Humboldt penguins found that the levels of porphyrins were directly correlated with the concentrations of As, Pb, and Cu, thus there exists a high probability that these penguins might develop hepatic and renal damage because of the exposure to these metals (Celis et al. 2014). The higher concentrations of metals in penguin excreta suggest a physiological mechanism of detoxification (Ancora et al. 2002), although this may also imply that those trace elements are not absorbed at the intestinal level. It has been observed that when birds present renal damage caused by Cd, the levels of this metal in excreta are increased (Goyer 1997). Lead concentrations in all of the biotic matrices of penguins studied are lower than those Pb levels found in marine, aquatic, and terrestrial birds of the Northern Hemisphere, which is highly industrialized and where human population is concentrated.

3.2 Essential Trace Elements

3.2.1 Copper

In general, there are not enough data available on the toxicity of Cu to avian wildlife. Birds, when compared to lower forms (fish, amphibians) are relatively resistant to Cu (Eisler 1998). With the exception of excreta, the maximum concentrations of Cu have been found in the liver of gentoo penguins from King George Island (386.1 μg/g, Table 5). In contrast, the lowest concentration of Cu (0.06 μg/g) has been reported in bones of Adélie penguins from the same location (Table 3). There is evidence showing that Cu levels of 1050 μg/g in the livers of eiders can cause liver necrosis and fibrosis (Norheim and Borch-Iohnsen 1990). In pygoscelid penguins, Cu levels over 24 μg/g in the liver (Szefer et al. 1993) could represent an additional stress to birds already facing stressful conditions, such as starvation (Debacker et al. 2000).

In feathers, Cu concentrations (6.87–20.89 μg/g, Table 1) are highest in adult gentoo penguins from O'Higgins Base (Celis et al. 2015b), whereas they are lowest in juveniles of the same species from King George Island (Jerez et al. 2013b). Levels of Cu in penguin feathers are higher than those concentrations found in feathers of different seabirds (7.56–11.2 μg/g) of the Northern Hemisphere (Kim et al. 1998; Malinga et al. 2010).

In eggshells, Cu concentrations in penguins are scarce and there is a single study (1.24 ± 0.4 μg/g, Table 2) in gentoo penguins from Livingston Island (Metcheva et al. 2011). Copper concentrations in penguin eggshells are comparable to those Cu levels reported in eggshells of birds from other latitudes (0.42–7.54 μg/g) (Dauwe et al. 2000; Yin et al. 2008; Kim and Oh 2014a).

In bones, Cu concentrations (0.06–1.15 μg/g, Table 3) are highest in colonies of Gentoo penguins from Byers Peninsula (South Shetland Islands). Concentrations of Cu in penguin bones are lower than those Cu levels found in bones of marine, aquatic, and terrestrial birds of the Northern Hemisphere (0.37–60 μg/g) (Lebedeva 1997; Kim et al. 1998; Orłowski et al. 2007; Yin et al. 2008).

In kidneys, Cu has been reported between 1.6 and 19.99 μg/g (Table 4), with the highest concentrations in Gentoo penguins from King George Island, whereas the lowest levels correspond to Adélie penguin from Potter Cove (King George Island). Levels of Cu in penguin kidneys are lower than those found in kidneys of Artic seabirds (12.2–27.8 μg/g) (Kim et al. 1998; Malinga et al. 2010).

In livers, Cu concentrations (10.91–386.1 μg/g, Table 5) are highest in colonies of gentoo penguins from King George Island, and are lowest in Adélie penguins from the same location. The levels of Cu in livers of Antarctic penguins are higher than those detected in other seabirds of Asia and Europe (0.26–92.5 μg/g) (Kim and Koo 2007; Pérez-López 2005; Ribeiro et al. 2009; Malinga et al. 2010). A study found that mute swans (*Cygnus olor*) from estuaries in Britain had more than 2000 μg/g of Cu in their blackened livers (Bryan and Langston 1992).

In muscles, Cu concentrations (4.43–9.95 μg/g, Table 6) are highest in colonies of gentoo penguins from King George Island (Jerez et al. 2013a), whereas they are lowest in Adélie penguins from King George Island (Jerez et al. 2013b). Levels of Cu in penguin muscles are within the range reported in the muscles of seabirds from Northern Hemisphere (3.59–18.3 μg/g) (Kim et al. 1998; Malinga et al. 2010; Orłowski et al. 2007).

In stomachs, Cu levels (4.85–66.42 μg/g, Table 7) presented the highest value in Adélie penguins from Avian Island, and the lowest levels in the same species from King George Island. The levels of Cu in penguin stomach contents are higher than those detected in seabirds of the Northern Hemisphere (4.89–14.0 μg/g) (Kim et al. 1998; Kim and Oh 2014b).

In excreta, Cu concentrations (37.6–585.8 μg/g) are highest in colonies of Adélie penguins from Kopaitic Island, and are lowest in chinstrap penguin from the Antarctic Peninsula (Table 8). Levels of Cu in penguin guano are higher than those values (10–150.8 μg/g) found in excrement birds from other parts of the world (Dauwe et al. 2000; Yin et al. 2008; Kler et al. 2014). A study in excreta of Humboldt penguins found that the levels of porphyrins were directly correlated with the concentrations of As, Pb, and Cu (Celis et al. 2014), and those birds might present some hepatic and renal disorder (Casini et al. 2003).

In blood, Cu concentrations (2.14–2.48 μg/g, Table 9) are only reported in little penguins from Australia. Copper concentrations in penguin blood are within the range reported in the seagulls, eiders, and ducks of the Northern Hemisphere (0.64–2.56 μg/g) (Franson et al. 2003; Kim et al. 2013).

In general, marine birds retain a very small portion of Cu and other metals ingested (Bryan and Langston 1992). Although Cu is an essential metal, in excess it can produce a series of metabolic, pulmonary, hepatic, and renal toxic effects (Soria et al. 1995). Copper can increase the toxic effects caused by Pb in birds, fishes, and invertebrates (Eisler 1988). In birds, Cu is accumulated in the liver and bone marrow, being associated with metallothionein and thus preventing an excess of free ions of this element (Eisler 1998). However, this protective mechanism is limited and lesions can be produced in the liver (ATSDR 2004).

3.2.2 Manganese

Excepting excreta and stomach contents, the maximum concentrations of Mn have been found in bones (18.35 μg/g, Table 3) and the liver (15.83 μg/g, Table 5) of gentoo penguins from Byers Peninsula and Adélie penguins from King George Island, respectively. In contrast, the lowest concentration of Mn (<0.01 μg/g) has been reported in feathers of juvenile Adélie penguins from Avian Island, Antarctica (Table 1).

In feathers, Mn concentrations range <0.01–3.26 μg/g (Table 1), with the highest levels in chinstrap penguins at Deception Island and the lowest in Adélie penguins at Avian Island. This range in penguin feathers is lower than those found in seabirds from the Northern Hemisphere (0.003–19.29 μg/g) (Burger et al. 2008; Kim et al. 2013), and also is lower than Mn levels detected in feathers of adult seabirds from industrialized and populated areas, such as the Brazilian coasts (11.4 μg/g, Barbieri et al. 2010).

In eggshells, there is only one study reporting concentrations of Mn (0.82 ± 0.08 μg/g, Table 2) in gentoo penguins from Livingston Island (Metcheva et al. 2011). Manganese concentration in penguin eggshells is within the range reported in the seabirds of the United States and Spain (0.29–4.63 μg/g) (Gochfeld 1997; Morera et al. 1997).

In bones, Mn concentrations (2.5–18.35 μg/g, Table 3) are highest in gentoo penguins from Byers Peninsula (Barbosa et al. 2013), and are lowest in the same species from Livingston Island (Metcheva et al. 2010). Concentrations of Mn in bones of penguins are within the range reported in the bones of marine, aquatic, and terrestrial birds of the Northern Hemisphere (1.06–30.6 μg/g) (Lebedeva et al. 1997; Kim et al. 1998).

In kidneys, Mn concentrations (3.78–11.18 μg/g, Table 4) are highest in chicks of Adélie penguins from King George Island during the 2008–2009 austral summer season, and are lowest in adult Adélie penguins from the same location during austral summers of 2007–2010. Manganese concentrations are higher in penguin chicks than those of adult specimens. Although Mn levels detected in individuals of the same species seem to show a temporal variability, the age of the birds seems to be relevant; birds regulate Mn primarily by excretion in the feces (Kler et al. 2014), and probably Mn intake from food in chicks exceeds excretion (Skoric et al. 2012). Concentrations of Mn in penguin kidneys are within the range found in the kidneys of Arctic seagulls (<0.01–20.1 μg/g; Malinga et al. 2010).

In the liver, Mn concentrations (6.8–15.83 μg/g, Table 5) are highest in Adélie penguins from King George Island and are lowest in the same species from the Antarctic Peninsula. Levels of Mn in penguin livers are comparable to values reported in seabirds from Asia and Artic (4.14–20.3 μg/g) (Kim et al. 1998; Malinga et al. 2010).

In muscles, Mn concentrations (0.46–2.55 μg/g, Table 6) are highest in chinstrap penguins from Deception Island and are lowest in gentoo penguins from the Antarctic Peninsula. Concentrations of Mn in penguin muscles are slightly lower than the concentrations of Mn in muscle tissues of Arctic birds (1.84–2.56 μg/g) (Campbell et al. 2005; Burger et al. 2008).

In the stomach, Mn levels (2.20–82.43 μg/g, Table 7) are highest in gentoo penguins from King George Island and are lowest in Adélie penguins from Avian Island. The levels of Mn in penguin stomach contents are higher than those of Mn (0.98–15.9 μg/g) detected in stomach contents of seabirds from the Northern Hemisphere (Kim et al. 1998; Kim and Koo 2007).

In excreta, Mn levels (12.3–138 μg/g, Table 8) are highest in chinstrap penguins from the Antarctic Peninsula and are lowest in gentoo penguins from Livingston Island. Concentrations of Mn in penguin droppings are within the range (0.03–221.8 μg/g) found in the guano of different avian species from Asia (Lebedeva et al. 1997; Kaur and Dhanju 2013; Kler et al. 2014).

In animals, Mn is a neurotoxic metal that can affect several neural activities, and at concentrations of about 1000 μg/g, it has negative effects on certain brain functions (Šaric and Lucchini 2007). Mn is distributed via blood linked to proteins (eg. albumin), being accumulated in tissues rich in mitochondria, such as hepatic and renal tissue (Erikson and Aschner 2003; Soria et al. 1995). Effects produced by an acute exposure to Mn include irritation in the digestive tract, respiratory disorders, cardiac ailments, coma, and even death (Soria et al. 1995). In turn, chronic intoxication with this metal generates neurological, reproductive, pulmonary, and immune alterations (ATSDR 2008). The elimination of Mn is produced mainly through the gastrointestinal tract (Roth 2006).

No research has been done related to the effects of Mn on penguins. It is an issue because increases in the environmental Mn levels have been related to the current use of Mn as additive in combustibles (Burger and Gochfeld 2000b). There is recent evidence showing that Mn levels in hepatic tissues of Antarctic penguins (Jerez et al. 2013a) are slightly higher than those detected two decades ago (Honda et al. 1986; Szefer et al. 1993).

3.2.3 Zinc

With the exception of excreta, the maximum concentrations of Zn (330.3 μg/g) have been found in livers of chinstrap penguins from King George Island (Table 5) and in bones of the same species from Byers Peninsula, Antarctica (Table 3). In contrast, the lowest concentration of Zn (4.07 μg/g) has been reported in eggshells of gentoo penguins from Livingston Island, Antarctica (Table 2).

In feathers, the range of Zn concentrations (33.26–119.72 μg/g, Table 1) indicates that the highest concentrations are in adult gentoo penguins from King George Island (Jerez et al. 2013a) and the lowest are in juvenile same species from Doumer Island. Zn levels in penguin feathers are similar to those Zn levels found in feathers of different seabirds of the Northern Hemisphere (42.9–189.2 μg/g) (Kim et al. 1998, 2013; Ribeiro et al. 2009; Lucia et al. 2010).

In eggshells, studies on Zn in penguins are not abundant. Zinc concentrations (4.07–8.3 μg/g, Table 2) are highest in Adélie penguins from Admiralty Bay, and are lowest in gentoo penguins from Livingston Island, South Shetland Islands. The levels of Zn in penguin eggshells are lower than those detected in water birds and seabirds of the United States and the Artic (9.04–58.1 μg/g) (Custer et al. 2007; Malinga et al. 2010).

In bones, the range of Zn (81–244.6 μg/g, Table 3) indicates the highest concentrations are in gentoo penguins from Byers Peninsula, whereas the lowest concentrations are in the same species from Livingston Island. The concentrations of Zn in penguin bones are similar to those Zn levels reported in bones of marine birds of the Northern Hemisphere (83.9–202 μg/g) (Kim et al. 1998; Yin et al. 2008; Skoric et al. 2012).

In kidneys, Zn concentrations (85.74–234.3 μg/g, Table 4) are highest in Adélie penguins from Avian Island. In contrast, the lowest Zn concentrations are in the same species from King George Island. Levels of Zn in penguin kidneys are higher than those Zn levels found in kidneys of marine birds from the North Pacific and Artic seabirds (30.2–183 μg/g) (Kim et al. 1998; Sagerup et al. 2009; Malinga et al. 2010).

In the liver, Zn concentrations (72–330.34 μg/g, Table 5) are highest in chinstrap penguins from King George Island, and are lowest in gentoo penguins from Livingston Island. Concentrations of Zn in penguin livers are above those Zn levels found in seabirds of the Northern Hemisphere (14.92–541 μg/g) (Parslow et al. 1973; Kim and Koo 2007; Pérez-López et al. 2005). A study found that a high concentration of Zn (541 μg/g) in livers of northern gannets (*Morus bassanus*) could be the main cause of the bird's mortality (Parslow et al. 1973).

In muscles, Zn concentrations (24–163.75 μg/g, Table 6) indicate the highest concentrations are in Adélie penguins from King George Island, while the lowest concentrations are in gentoo penguins from Livingston Island. Levels of Zn in seabirds (53.2–75.5 μg/g) of the Northern Hemisphere (Kim et al. 1998; Malinga et al. 2010) are within the range found in the penguin muscles.

In stomachs, Zn levels (19.84–71.16 μg/g, Table 7) are highest in Adélie penguins from King George Island, and are lowest in gentoo penguins from the same location. Concentrations of Zn in penguin stomach contents are within the range (6.64–102 μg/g) found in the seabirds of the Northern Hemisphere (Kim et al. 1998; Kim and Koo 2007).

In excreta, the range of Zn (0.83–487.1 μg/g, Table 8) shows the highest concentrations in Humboldt penguins from Pan de Azúcar Island, while the lowest levels are in the same species from Cachagua Island. Concentrations of Zn in penguin droppings are lower than those (100–721.8 μg/g) found in marine birds and different avian species of the Northern Hemisphere (Yin et al. 2008; Kaur and Dhanju 2013).

In blood, only a single study has measured Zn levels in little penguins (33.47–38.77 μg/g, Table 9). These levels are within the range detected in the long-tailed ducks (*Clangula hyemalis*) and nesting common eiders (*Somateria mollissima*) from Alaska (18.2–39 μg/g) (Franson et al. 2003).

Despite the fact that Zn is an essential metal, some pancreas histological damage has been detected in birds at high Zn levels (Eisler 1993). In birds, Zn accumulated in liver bonded to metallothionein, though it can also be accumulated in muscles and bones (Wastney et al. 2000). In seabirds, there is a significant positive correlation between renal Zn and Cd, which evidences a possible effect of metallothionein synthesis caused by Cd accumulation (Honda et al. 1990; Malinga et al. 2010). Evidence shows that Zn poisoning in birds usually occurs when the concentration of this metal exceeds 2100 μg/g in the liver or kidney (Eisler 1993). The concentrations of Zn in livers of penguins are below 200 μg/g (Table 5), considered as the threshold value of physiological importance in different species of seabirds (Honda et al. 1990), except that found in liver of chinstrap penguins (330.3 μg/g) and in livers of gentoo penguins (237.2 μg/g) from King George Island. These levels of Zn seem to be related to the great concentration of human activities present in King George Island (Tin et al. 2009).

4 Similarities and Differences of Trace Elements

4.1 Distribution of Trace Elements

There is great similarity (82%) between concentrations of trace elements in guano and stomach contents of penguins (Fig. 2). Likewise, the levels of trace elements in

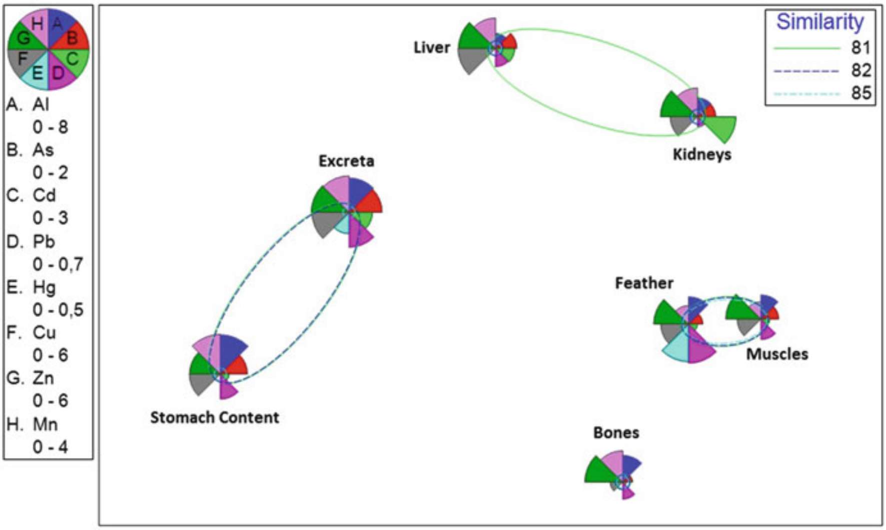

Fig. 2 Bubble chart for mean concentrations of metals in different biological matrices of *Pygoscelis papua* reported from South Shetland Islands. Data taken from Barbosa et al. (2013), Brasso et al. (2014), Celis et al. (2015b), Espejo et al. (2014), Jerez et al. (2011), Jerez et al. (2013a, b), Metcheva et al. (2006, 2010, 2011), Santos et al. (2006), Yin et al. (2008)

kidneys and livers present great similarity (81%), which may be due to the fact that both organs have similar mechanisms of detoxification and biotransformation of elements (Sánchez-Virosta et al. 2015). Furthermore, there is also 85% similarity between the concentrations of trace elements in feathers and muscles. Due to sampling constraints, it is not easy to establish relationships between the concentrations in feathers and the concentrations found in the internal tissues of penguins, even though some previous works have found some relationship between feathers and muscle tissues for some trace elements in birds (Del Hoyo et al. 1992). Metal levels in eggs and bones presented no correlation with the other biotic matrices. Some metals (as Pb, Cd) are not metabolically regulated and tend to be immobilized in bird bones (Lebedeva 1997) and eggshells (Kim and Oh 2014a). Both biological matrices are mainly composed of Ca, which is one of the most important plasma constituents in mammals and birds, and provides structural strength and support to bones and eggshells (De Matos 2008). Trace elements such as Pb and Cd might interact with the metabolic pathway of Ca (Scheuhammer 1987).

A high content of elements in penguin excreta imply a physiological mechanism of detoxification (Ancora et al. 2002), but also imply that elements are not necessarily absorbed at the intestinal level, which reinforces the fact that high concentrations of trace elements in feces are likely the result of low intestinal absorption rather than detoxification mechanisms, and much of the elements ingested by these seabirds are being excreted. It is observed that when some bird present renal damage caused by Cd, the levels of this metal in excreta is increased (Goyer 1997). In penguins, feathers play an important role in detoxification of Hg and Pb, because a large amount of these metals from their diets can be transferred into their plumages (Stewart et al. 1997; Ancora et al. 2002; Jerez et al. 2011). Other metals such as Cd, Cu, and Zn are mainly eliminated via the feces (Ancora et al. 2002; Yin et al. 2008). In general, sequestration of metals (such as Hg or Pb) in bird's feathers results in decreased internal bioavailability (Jerez et al. 2011; Calle et al. 2015). Diet, exposure levels, physiological conditions, and the toxic-kinetic mechanisms regulate the arrival of metals to feathers, as in the case of Hg (Becker et al. 2002). Redistribution to plumage occurs during feather growth when the feather is connected to blood vessels, and metals are incorporated in the keratin structure (Burger et al. 2011). When the feather matures, blood vessels shrivel, and the feather is no longer supplied with blood, at which point metal deposition to the feather ceases (Burger 1993). Hg elimination is possible via deposits in eggs, excreta, uropygial gland, and feathers (Dauwe et al. 2000). In seabirds, Hg concentrations in feathers reflect the uptake and storage of this heavy metal during the period between molts rather than short-term uptake (Furness et al. 1986).

In general, trace element levels in penguins are scarce and fragmented; therefore, no correlation analysis is possible now. Data of trace elements available in *Pygoscelis* penguins of the South Shetland Islands indicate that the levels of Cd in gentoo, chinstrap, and Adélie penguins that live there are strongly influenced by diet, which has also been noted in populations of seagulls from the Northern Hemisphere (Kim and Oh 2014c). In birds, trace element levels in blood reflect recent dietary exposure and often correlate strongly with those in internal tissues (Monteiro and Furness 2001). A study evidenced that blood provides a more precise indicator of penguin body burden for Al, As, Cd, Cu, Fe, Hg, Pb, Se, and Zn than feathers (Finger et al. 2015).

At present, most Hg pollution resides in aquatic environments, where it is converted to methylmercury (Chen et al. 2008). Because of its high affinity with sulfydryl groups of proteins, this heavy metal is easily incorporated into the food chain, bioaccumulating in aquatic organisms, and bioamplifying from one trophic level to the next (Fitzgerald et al. 2007). Some metals such as Zn and Cd among others might be biomagnified under certain environments such as Antarctica, a cold place where trophic chains are short and highly dependent on krill (Majer et al. 2014). The whole trophic transference coefficient (TTC) for gentoo penguins at King George Island is 0.01 for Al, 0.21 for As, 39.55 for Cd, 0.21 for Pb, 1.45 for Cu, 6.90 for Zn, and 0.05 for Mn (no data were available for Hg levels in stomach contents of the species at that location). The value of TTC is usually <1 for trace metals (Anan et al. 2001), except for those metals highly cumulative in the organism which are biomagnified in the trophic chain, such as Hg (Lavoie et al. 2013). Cd and Zn showed a high cumulative power in gentoo penguins, with TTC values far above unity. Scientific evidence indicates that Zn, Se, Cu, and Cd tend to bioaccumulate in aquatic trophic chains (Dehn et al. 2006; Mathews and Fisher 2008). This suggests the possibility of metal biomagnification under specific circumstances. It has been found that biomagnification of Hg is expressed more strongly in cold environments with simple trophic chains (Lavoie et al. 2013). This issue should be addressed in depth in further studies, considering the diversity of marine environments in which the different species of penguins feed.

4.2 Geographical Differences

Most studies of levels of trace elements in penguins (Table 10, Fig. 3) have been carried out in Antarctica and nearby islands. The most reported trace elements are Pb, Cd, Cu, and Zn. In contrast, Al and Mn are the least reported elements. The lack of studies on trace elements in penguins from the coasts of Australia, South Africa, and Galapagos Islands is clearly noted. Most of the field studies of trace elements are concentrated in the Antarctic and subantarctic areas (>85%), specifically in the Antarctic Peninsula and South Shetland Islands; the rest of the studies are concentrated in the coasts of South America, Subtropical Front (Indian Ocean), and coasts of Australia. Further studies are needed in order to overcome the huge gap of data between Antarctica and other territories of more temperate zones where there are colonies of other species of penguins. Differences in trace element concentrations in the same species at different sites are evidenced in gentoo penguins, because they have a large distribution and a very plastic diet depending on site. Gentoo penguins at Crozet Islands have higher feather Hg concentrations (Carravieri et al. 2016) than those reported at Antarctic locations (Bargagli et al. 1998). Gentoo penguins at subantarctic areas have higher feather Hg concentrations than those reported at Antarctic locations (Table 1). Gentoo penguins at higher latitudes feed largely on krill (Carlini et al. 2009), whereas they prey mainly on fish at lower latitudes (Lescroël et al. 2004). Krill is a pelagic low-trophic prey very abundant in Antarctica with lower Hg burden compared to fish (Bargagli et al. 1998; Bustamante et al. 2003).

Due to the lack of data, the comparison of the levels of trace elements among different species and populations of penguins must be taken with caution. In general, the concentrations of trace elements are fragmented from the spatio-temporal point of view, which prevents for now conducting an analysis of tendencies. Hence, the implementation of monitoring programs that incorporate these variables is required.

4.3 Interspecific Differences

There are 18 species of penguins that inhabit the planet (García and Boersma 2013), but trace metals have been reported only in 11 species, evidencing the information gap in species such as *Eudyptes pachyrhynchus, Eudyptes sclateri, Eudyptes robustus, Eudyptes schlegeli, Spheniscus demersus, Spheniscus mendiculus,* and *Megadyptes antipodes.* The species with more elements reported are *P. papua*,

Table 10 Locations and number of studies performed on trace elements in different species of penguins worldwide

Region	Location	Ψ	Coordinates	Studies[a]	Metals reported	References
West Antarctica	Barton peninsula	1	62°14′S, 58°46′W	1	Pb, Hg	Yin et al. (2008)
	Potter cove	2	62°14′16″S, 58°39′59″W	1	As, cd, Pb, Hg, cu, Mn	Smichowski et al. (2006)
	Stranger point	3	62°15′32.00″S, 58°36′54.00″W	1	Cd, Pb, cu, Zn, Mn	Celis et al. (2015b)
	Arctowski	4	62° 9′36″S, 58°28′25″W	1	As, cd, Pb, Hg, cu, Zn	Celis et al. (2015a)
	King George Island	5	62°02′S, 58°21′W	4	Al, as, cd, Pb, Hg, cu, Zn, Mn	Brasso et al. (2014); Jerez et al. (2013a, b)
	Admiralty Bay	6	62° 4′52″S, 58°23′41″W	1	Hg, Zn	Santos et al. (2006)
	Narebski point	7	62°12′S, 58°45′W	1	As, cd, Pb, Hg, cu, Zn	Espejo et al. (2014)
	Fildes peninsula	8	62°12′S, 58°58′W	1	Pb, Hg	Yin et al. (2008)
	Yankee Harbor	9	62°31′60.00″S, 59°46′41.0″W	1	As, cd, Pb, cu, Zn	Espejo et al. (2014)
	Livingston Island	10	62°37′S 60°27′W	4	Al, as, cd, Pb, cu, Zn, Mn	Metcheva et al. (2006, 2010, 2011); Jerez et al. (2011)
	Cape Shirreff	11	62°28′S, 60°47′W	1	As, cd, Pb, cu, Zn	Espejo et al. (2014)
	Byers peninsula, Livingston is.	12	62°38′S, 61°05′W	1	Al, as, cd, Pb, cu, Zn, Mn	Barbosa et al. (2013)
	Hannah point, Livingston is.	13	62°39′16″S, 60°36′48″W	1	Al, as, cd, Pb, cu, Zn, Mn	Barbosa et al. (2013)
	Deception Island	14	62°56′27″S, 60°35′39″W	3	Al, as, cd, Pb, cu, Zn, Mn	Jerez et al. (2011); Jerez et al. (2013a, b)

(continued)

Table 10 (continued)

Region	Location	Ψ	Coordinates	Studies[a]	Metals reported	References
	O'Higgins Base	15	63°19′15″S, 57°53′55″W	3	Al, as, cd, Pb, Hg, cu, Zn, Mn	Celis et al. (2012); Espejo et al. (2014), Celis et al. (2015b)
	Kopaitic	16	63°18′59″S, 57°54′47″W	2	As, cd, Pb, Hg, cu, Zn	Celis et al. (2015a), Espejo et al. (2014)
	Mikkelsen Harbor	17	63°53′22″S, 60°47′3″W	1	As, cd, Pb, Hg, cu, Zn	Espejo et al. (2014)
	Hydrurga rocks	18	64° 8′40″S, 61°40′22″W	1	As, cd, Pb, cu, Zn	Espejo et al. (2014)
	Danco Island	19	64°43′53″S, 62°35′44″W	1	As, cd, Pb, cu, Zn	Espejo et al. (2014)
	Ronge Island	20	64°43′S, 62°41′W	1	Al, as, cd, Pb, cu, Zn, Mn	Jerez et al. (2011)
	Neko Harbor	21	64°50′S, 62°33′W	1	Cd, Pb, cu, Zn, Mn	Celis et al. (2015b)
	González Videla Base	22	64° 49′ 26″ S, 62° 51′ 26″ W	2	As, cd, Pb, Hg, cu, Zn	Celis et al. (2012); Espejo et al. (2014)
	Brown Station	23	64°53′43.2″S, 62°52′13.7″W	1	As, cd, Pb, cu, Zn	Espejo et al. (2014)
	Paradise Bay	24	64°53′S, 62°53′W	1	Al, as, cd, Pb, cu, Zn, Mn	Jerez et al. (2011)
	Yalour Island	25	65°14′2″S, 64°13′26″W	2	Al, as, cd, Pb, Hg, cu, Zn, Mn	Jerez et al. (2011); Celis et al. (2015a)
	Yelcho Station	26	64°52′33″S 63°35′02″W	1	As, cd, Pb, cu, Zn	Espejo et al. (2014)
	Doumer Island	27	64°51′S, 63°35′W	1	Cd, Pb, cu, Zn, Mn	Celis et al. (2015b)

	Avian Island	28	67°46′12″S, 68°53′40″W	2	Al, as, cd, Pb, Hg, cu, Zn, Mn	Celis et al. (2015a); Jerez et al. (2013a)
	Weddell Sea	29	77°S 49°W	1	Cd, cu	Steinhagen-Schneider (1986)
East Antarctica	Edmonson point	30	74°20′S 165°8′E	1	Cd, Pb, Hg	Ancora et al. (2002)
	Terra Nova Bay	31	74°47′30″S, 164°51′35″E	1	Hg	Bargagli et al. (1998)
	Adélie land	32	66°40′ S, 140°01′ E	1	Hg	Carravieri et al. (2016)
	Zhongshan Station	33	69°22′ S, 76°22′ E	1	Pb, Hg	Yin et al. (2008)
West coast of South America	Pan de Azúcar is., Chile	34	26° 9′S, 70°41′29″W	1	As, cd, Pb, Hg, cu, Zn	Celis et al. (2014)
	Chañaral is., Chile	35	29° 1′33″S, 71°34′5″W	1	As, cd, Pb, Hg, cu, Zn	Celis et al. (2014)
	Cachagua is., Chile	36	32°35′6″S, 71°27′24″W	1	As, cd, Pb, Hg, cu, Zn	Celis et al. (2014)
East Coast of South America	Rio Grande do Sul, Brazil	37	31°11′20″S, 50°51′47″W	1	Cd, Pb, Hg	Kehrig et al. (2015)
	Punta Tombo, Argentina	38	44° 2′17″S, 65°12′2″W	1	Hg	Frias et al. (2012)
Subantarctic zone	South Georgia is.	39	54° 16′ 53″ S, 36° 30′ 28″ W	1	Hg	Pedro et al. (2015)
	Crozet Islands	40	46°26′S, 51°45′E	2	Hg	Scheifler et al. (2005); Carravieri et al. (2016)
	Kerguelen Islands	41	49°21′S, 70°18′E	1	Hg	Carravieri et al. (2013)
Subtropical front, Indian Ocean	Amsterdam Island	42	37°50′ S, 77°31′ E	1	Hg	Carravieri et al. (2016)
Coast of Australia	Victoria	43	38°48′53″S, 146° 5′36″E	1	Al, as, cd, Pb, Hg, cu, Zn	Finger et al. (2015)

Ψ Number of the position pointed in Fig. 3
[a]Number of studies performed

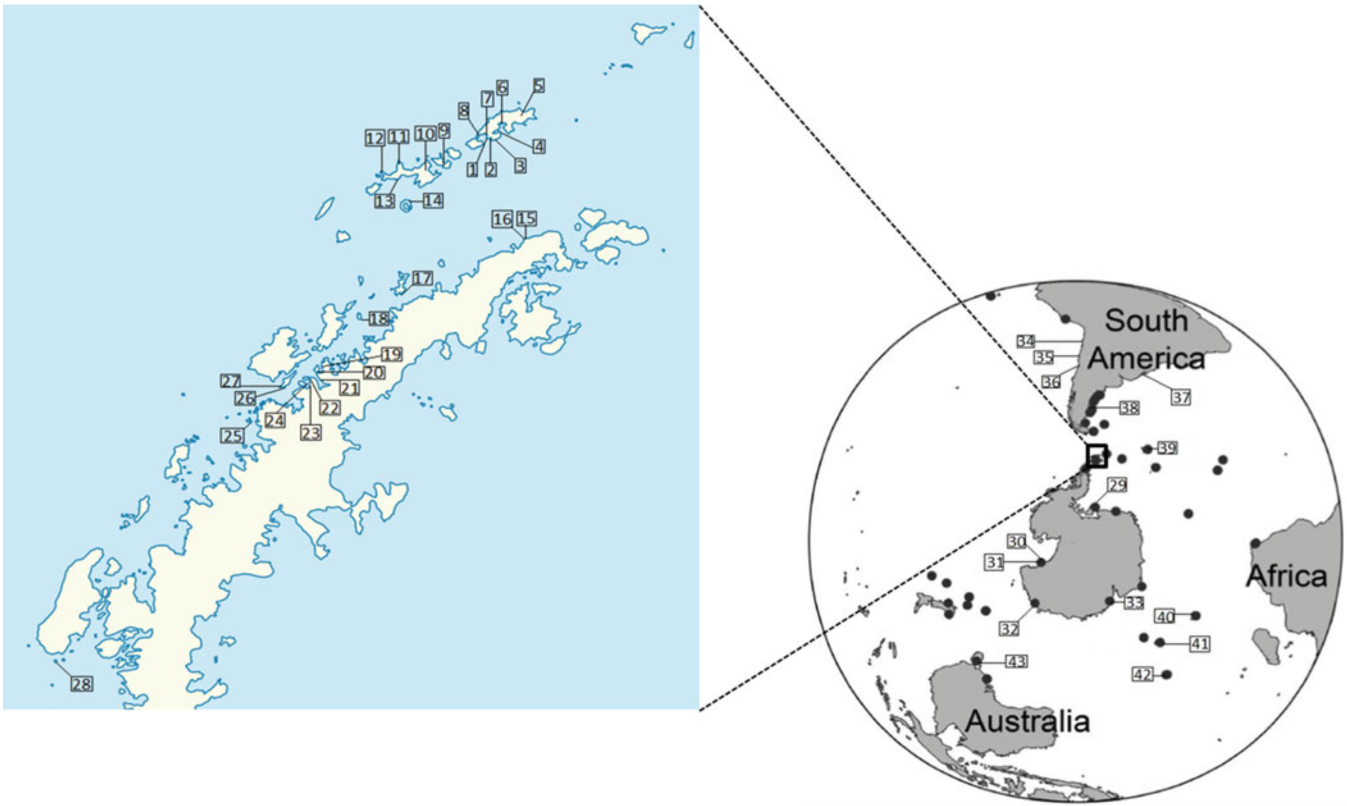

Fig. 3 Geographical distribution of trace metals reported in penguins. Each number is associated with the information given in Table 10

P. adeliae, and *P. antarctica*. On the other hand, the least studied species are *E. chrysocome* and *E. chrysolophus*. It is necessary to state that the distribution of trace elements by species from different studies, species, and individuals presents serious limitations because of temporal variation, spatial variation, diet, individual specialization, physiological condition, and sex.

In Adélie, gentoo, and chinstrap penguins, concentrations of the essential trace elements Cu, Mn, and Zn in all biotic matrices exhibited less inter-species variation than the non-essential Al, As, Cd, Hg, and Pb, expressed through the coefficient of variation. These results are in agreement with similar findings of other investigations in seabirds (Honda et al. 1990; Lock et al. 1992). Penguins, by virtue of their members exhibiting a wide range of trace element burdens, along with variation in diet, varying moult strategies and variation in their average life spans may explain inter-species pattern of metal accumulation, storage, and elimination (Thompson 1990; García and Boersma 2013). This is an issue that needs to be investigated more.

Diet is one of the most important factors that explain differences in trace element concentrations among the species. Penguins are useful bioindicators of Hg contamination in their food webs (Carravieri et al. 2016). Feather Hg concentrations in *Eudyptes* and *Pygoscelis* penguins are lower than *Aptenodytes* penguins, because they feed at lower trophic levels (Carravieri et al. 2013). One study showed that the concentrations of Zn, Al, and Mn in feathers were significantly higher in gentoo than in chinstrap penguins, which could be explained by the different diet and feeding habits of these species (Metcheva et al. 2006). During the Antarctic summer, when the breeding season takes place, gentoo penguins feed inshore, eating mainly crustaceans (68%) and fish (32%), even though foraging areas may also be included in their diet (Croxall et al. 1997). Also chinstrap penguins feed almost exclusively on krill, but can feed beyond the continental shelf areas (Espejo et al. 2014). Concentration of trace elements can differ among colonies of the same species that live far from each other owing to diet and the presence of chemicals in waters (Jerez et al. 2011). Similarly, Yin et al. (2008) mention that the difference in Cu levels among seabirds might be related to different food resources for the species. The trophic level of the species which is given by diet can be determined by means of stable isotopes of nitrogen, a method infrequently used in studies of trace elements in penguins (Brasso and Polito 2013; Brasso et al. 2014; Carravieri et al. 2016).

5 Summary and Conclusions

In the environment, trace elements are persistent and come from both natural cycling in the biosphere and anthropogenic activities (Nordberg and Nordberg 2016). For this reason there is a concern about the possible negative effects these contaminants may have on animals and marine ecosystems (Szopińska et al. 2016). Birds are excellent indicators of the degree of pollution in the environment, because they rapidly express the biological impacts of the contaminants that can even be extrapolated to humans (Ochoa-Acuña et al. 2002; Cifuentes et al. 2003; Zhang and Ma 2011), a remarkable issue considering humans are the most sensitive species to the toxic effects of some trace elements (Byrns and Penning 2011). The human population will increase and also increase marine-derived protein consumption. Most penguins include fish in their diets, such as sprats, myctophid fish, anchovies, silversides, jack mackerel, and common hake, among others (García and Boersma 2013). Many fishes are also consumed by humans, thus these birds might be used as a bioindicator for human health and as exposure assessment. Most penguins are on the upper side of the trophic chain and they depend on few species for food. Consequently, the effects on a particular species might loom as a serious threat to penguins.

Investigations of trace elements in penguins report mostly the levels of Al, As, Cd, Cu, Hg, Mn, Pb, and Zn. The most reported metal is Pb, whereas Al is the least reported. Other metals such as Co, Cr, Fe, or Ni have been poorly studied (Jerez et al. 2013a; Szopińska et al. 2016). The oldest data dates back to the 1950s and it was aimed at determining the Hg levels in feathers of King penguins (*Aptenodytes patagonicus)* from Crozet Islands, South East of Indian Ocean (Carravieri et al. 2016).

There are 18 species of penguins around the world and trace elements have been reported in 11 of them (*P. papua, P. antarctica, P. adeliae, Aptenodytes forsteri, A. patagonicus, Spheniscus magellanicus, S. humboldti, Eudyptes chrysolophus, E. chrysocome, E. minor,* and *E. moseleyi*). Most studies of concentrations of trace elements in penguins have been focused on the genus *Pygoscelis*, mainly on gentoo penguins, followed by Adélie penguins, and finally chinstrap penguins. Other penguin species such as *E. pachyrhynchus, E. sclateri, E. robustus, E. schlegeli, S. demersus, S. mendiculus,* and *Megadyptes antipodes* have not received any attention.

The most studied penguin biological matrices are feathers and then excreta, followed by the liver, kidneys, bones, muscles, and stomach contents. On the other hand, studies carried out to measure trace elements in blood and internal organs such as heart, testicles, spleen, or brains of penguins are scarce (Bargagli et al. 1998; Finger et al. 2015; Metcheva et al. 2010; Metcheva et al. 2011). The species which display the highest concentration of most trace elements are the gentoo penguin (33%), followed by the Adélie penguin (31%), the chinstrap penguin (19%), the Humboldt penguin (7%), the Magellanic penguin (6%), and the Emperor penguin (4%).

The maximum concentrations (μg/g, dw) of Al (2595) have been found in stomach contents of gentoo penguins from King George Island, and Cd (351.8) in the liver of Adélie penguins from Antarctic Peninsula. The highest levels of As (7.9) and Pb (12.8) were found in excreta of Humboldt penguins from the Central Coast of Chile. Maximum concentrations of Hg (6.6) and Cu (585.8) have been reported in excreta of gentoo penguin and Adélie penguin, respectively, both from the Antarctic Peninsula, whereas the maximum Zn levels (487.1) was found in excreta of Humboldt penguins of Northern Chile. Finally, excepting excreta and stomach contents, maximum levels of Mn (18.35) are in the bones of gentoo penguins from Byers Peninsula (South Shetland Islands). The large variation in trace element concentrations detected in different biotic matrices of penguins in Antarctica might be explained because in this continent many pristine places coexist with locations having major human presence, a situation which rarely occurs in others areas of the world. Additionally, several other factors can force variation in trace element concentrations in penguin tissues such as feeding ecology, physiological state, species, age class, molting patterns, among others.

In general, Hg, Pb, and Cd concentrations in penguins are lower than those reported in other seabirds from the Northern Hemisphere, whereas the concentrations of Al and As are otherwise. The concentrations of Cu, Mn, and Zn tend to be within the range reported in the marine birds of the Northern Hemisphere, suggesting that those elements are regulated in seabirds (Gibbs 1995). The highest levels of Cu and Cd correspond to penguins that live in Antarctica, which might be related to the high levels of these metals detected in the Antarctic krill (Nygard et al. 2001). On the other hand, it has been observed that in the Antarctic Peninsula there is a natural enrichment of Cd, As, and Al in the trophic chains, due to the local volcanism (Deheyn et al. 2005). Nevertheless, comparisons could be influenced by the differences in the diet composition of each of the species (Jerez et al. 2011).

Studies on the effects of trace elements on penguins are scarce. For that reason, the comparison of data reported in penguins with those obtained from studies performed on birds at other locations and ecologically different to penguins was unavoidable. Hence, any comparison to toxic thresholds of trace elements in terrestrial birds should be taken with extreme caution, because seabirds appear to be more resistant to toxic effect of most pollutants than are mammals or terrestrial birds (Beyer et al. 1996). In general, the concentrations of trace elements in the different organs of penguins are below the toxicity thresholds with negative biological consequences for seabirds. Some colonies of Humboldt penguins located in areas with human presence on the coast of Chile might present some pathological problems due to As, Cu, and Pb (Celis et al. 2014). Some negative effects in the liver and kidneys of gentoo penguins from the Antarctic Peninsula could be linked to local Pb contamination (Celis et al. 2012, Jerez et al. 2013a). Levels of Zn in livers of some colonies of gentoo and chinstrap penguins from King George Island (Jerez et al. 2013a) exceeded in 19% and 65% the threshold value of physiological importance for seabirds, respectively (Honda et al. 1990). It seems to be related to areas of greatest human activities in Antarctica, which are concentrated precisely on King George Island (Bargagli 2008; Tin et al. 2009). Levels of Cd in livers of some colonies of gentoo, Adélie, chinstrap, and Emperor penguins that inhabit the Antarctic Peninsula area, and Magellanic penguins from southern Brazil, which together represent almost 48% of the reported colonies might be associated with physiological and ecological problems (>3 μg/g, Scheuhammer 1987). Cadmium concentrations found in kidneys of Adélie, chinstrap, and Emperor penguin from some locations of the Antarctic Peninsula (270.2–351.8 μg/g, Table 4), such as Avian Island, Deception Island, and Weddell Sea, indicate that these birds have suffered some degree of chronic exposure to this metal (Furness 1996). Further studies that correlate the levels of trace metals found in non-invasive samples with biological effects on penguins are required.

Most studies of concentrations of trace elements in penguins have been carried out on the Antarctica and subantarctic islands, thus evidencing a lack of data from other areas where penguins live also, such as Australia, South Africa, South America, and Galapagos Islands. It is surprising to find studies mainly in Antarctica, since researchers require an adequate implementation and a firm determination to work under extreme climatic conditions. Perhaps the urge to travel to remote and poorly explored regions is more important than the simple desire of performing research in more populated places with more temperate climates where the species of threatened penguins could be more exposed to contaminants by being in areas with major human presence.

The trophic transfer coefficient, calculated from the levels of metals available in gentoo, chinstrap, and Adélie penguins, suggests a possible biomagnification of Cd and Zn. Due to the fact that scientists have always believed that metals, except Hg, are not biomagnified, this issue needs to be studied more in different environments inhabited by penguins.

Most studies of penguins have focused on measuring the levels of exposure in different biotic matrices. The concentration of metals in tissues and organs of penguins may have a great toxicological importance. In humans, diseases related to deficiency of essential trace elements are well known (Nordberg and Nordberg 2016). Further studies with biomarkers are needed in order to evaluate the actual risks associated with the levels of these contaminants in polar environments with low ecological diversity, which can increase diseases with consequences for the health of penguin populations (Boersma 2008).

Little is known about the interaction of metals that might activate certain detoxification mechanisms of the organism of penguins. It is suspected that Se could play an important role in the detoxification processes of Hg. The study with species in captivity could be a good alternative to evaluate the physiological mechanisms of these species at a given concentration of metals, under a controlled environment (Falkowska et al. 2013).

In the short term, studies of trace elements in penguins should take into account the following aspects:

- Incorporation of other metals such as Co, Ni, or Cr and their possible effects in the organisms of different species of penguins in order to perform more accurate risk assessments.
- Further toxico-kinetics studies of trace element levels in penguins, including other tissues and organs, are needed to better understand the overall toxicity in seabirds.
- Information on metals of the following species is crucial: *Eudyptes pachyrhynchus, Eudyptes moseleyi, Eudyptes sclateri, Eudyptes robustus, Eudyptes schlegeli, Spheniscus demersus, Spheniscus mendiculus,* and *Megadyptes antipodes.*
- Correlation between the levels of metals in different biological matrices with their effects on different species and geographic locations is required.

- Interspecific variation of metals should be addressed more in depth, with isotopes of nitrogen being a good tool to understand differences among species.
- The implementation of monitoring programs that incorporate spatial-temporal data is required for conducting an analysis of tendencies.
- It is crucial to implement uniform monitoring protocols to help unify the data and make it more comparable.

Acknowledgments Winfred E. Espejo is a graduate student at the Universidad de Concepción, Chile, who is sponsored by the CONICYT-Chile to pursue PhD research. This study was financially supported by the project INACH RG 09-14 (J. Celis), INACH T31-11 (G. Chiang), and FONDAP CRHIAM 15 13 0015 (R. Barra). Thanks also are given to project 216.153.025-1.0 of the Research Division of the Universidad de Concepción. Many thanks are also given to Dr. Evelyn Habit, Liseth Chaura, and peer reviewers for their useful suggestions. Finally, the authors also thank Diane Haughney for the English revision.

References

Agusa T, Matsumoto T, Ikemoto T, Anan Y, Kubota R, Yasunaga G, Kunito T, Tanabe S, Ogi H, Shibata Y (2005) Body distribution of trace elements in black-tailed gulls from Rishiri island, Japan: age-dependent accumulation and transfer to feathers and eggs. Environ Toxicol Chem 24:2107–2120

Anan Y, Kunito T, Watanabe I, Sakai H, Tanabe S (2001) Trace element accumulation in hawksbill turtle (*Eretmochelys imbricata*) and green turtle (*Chelonia mydas*) from Yaeyama Islands, Japan. Environ Toxicol Chem 20:2802–2814

Ancora S, Volpi V, Olmastroni S, Focardi S, Leonzio C (2002) Assumption and elimination of trace elements in Adélie penguins from Antarctica: a preliminary study. Mar Environ Res 54:341–344

Arcos JM, Ruiz X, Bearhop S, Furness RW (2002) Mercury levels in seabirds and their fish prey at the Ebro Delta (NW Mediterranean): the role of trawler discards as a source of contamination. Mar Ecol Prog Ser 232:281–290

ATSDR (2004) Toxicological profile for copper. Agency for Toxic Substances and Disease Registry US Department of Health and Human Services, Public Health Service, Atlanta, GA. http://wwwatsdrcdcgov/ToxProfiles/tp132pdf. Accessed 19 May 2016

ATSDR (2007) Toxicological profile for arsenic. Agency for Toxic Substances and Disease Registry US Department of Health and Human Services, Public Health Service, Atlanta, GA. http://wwwatsdrcdcgov/toxprofiles/tp2pdf. Accessed 19 May 2016

ATSDR (2008) Toxicological profile for manganese. Agency for Toxic Substances and Disease Registry US Department of Health and Human Services, Public Health Service, Atlanta, GA. http://wwwatsdrcdcgov/toxprofiles/tpasp?id=102&tid=23. Accessed 19 May 2016

Ballatori N (2002) Transport of toxic metals by molecular mimicry. Environ Health Perspect 110:689–694

Barbieri E, de Andrade PE, Filippini A, Souza dos Santos I, Borges CA (2010) Assessment of trace metal concentration in feathers of seabird (*Larus dominicanus*) sampled in the Florianópolis, SC, Brazilian coast. Environ Monit Assess 169:631–638

Barbosa A, De Mas E, Benzal J, Diaz J, Motas M, Jerez S, Pertierra L, Benayas J, Justel A, Lauzurica P, Garcia-Peña F, Serrano T (2013) Pollution and physiological variability in gentoo penguins at two rookeries with different levels of human visitation. Antarct Sci 25:329–338

Bargagli R (2001) Trace metals in Antarctic organisms and the development of circumpolar biomonitoring networks. Rev Environ Contam Toxicol 171:53–110

Bargagli R (2008) Environmental contamination in Antarctic ecosystems. Sci Total Environ 400:212–226

Bargagli R, Monaci F, Sánchez-Hernández J, Cateni D (1998) Biomagnification of mercury in an Antarctic marine coastal food web. Mar Ecol Prog Ser 169:65–76

Barjaktarovic L, Elliott JE, Scheuhammer AM (2002) Metal and metallothionein concentrations in scoter (*Melanitta* spp.) from the Pacific northwest of Canada, 1989–1994. Arch Environ Contam Toxicol 43:486–491

Becker PH, González-Solís J, Behrends B, Croxall J (2002) Feather mercury levels in seabirds at South Georgia: influence of trophic position, sex and age. Mar Ecol Prog Ser 243:261–269

Beyer WN, Heinz GH, Redmon-Norwood AW (1996) Environmental contaminants in wildlife: interpreting tissue concentrations. Lewis, Boca Raton, FL, p 512

Beyer NW, Spalding M, Morrison D (1997) Mercury concentrations in feathers of wading birds from Florida. Ambio 26:97–100

Beyer WN, Franson JC, Locke LN, Stroud RK, Sileo L (1998) Retrospective study of the diagnostic criteria in a lead-poisoning survey of waterfowl. Arch Environ Contam Toxicol 35:506–512

Boersma PD (2008) Penguins as marine sentinels. Bioscience 58:597–607

Brasso RL, Polito MJ (2013) Trophic calculations reveal the mechanism of population-level variation in mercury concentrations between marine ecosystems: case studies of two polar seabirds. Mar Pollut Bull 75:244–249

Brasso RL, Polito MJ, Emslie SD (2014) Multi-tissue analyses reveal limited inter-annual and seasonal variation in mercury exposure in an Antarctic penguin community. Ecotoxicology 23:1494–1504

Braune BM, Gaston AJ, Hobson KA, Gilchrist HG, Mallory ML (2014) Changes in food web structure alter trends of mercury uptake at two seabird colonies in the Canadian Arctic. Environ Sci Technol 48:13246–13252

Bryan GW, Langston WJ (1992) Bioavailability, accumulation and effects of heavy metals in sediments with special reference to United Kingdom estuaries: a review. Environ Pollut 76:89–131

Burger J (2008) Assessment and management of risk to wildlife from cadmium. Sci Total Environ 389:37–45

Burger J, Gochfeld M (1997) Risk, mercury levels, and birds: relating adverse laboratory effects to field biomonitoring. Environ Res 75:160–172

Burger J, Gochfeld M (2000a) Effects of lead on birds (*Laridae*): a review of laboratory and field studies. J Toxicol Environ Health B Crit Rev 3:59–78

Burger J, Gochfeld M (2000b) Metal levels in feathers of 12 species of seabirds from midway atoll in the northern Pacific Ocean. Sci Total Environ 257:37–52

Burger J, Gochfeld M, Sullivan K, Irons D, McKnight A (2008) Arsenic, cadmium, chromium, lead, manganese, mercury, and selenium in feathers of black-legged kittiwake (*Rissa tridactyla*) and black oystercatcher (*Haematopus bachmani*) from Prince William sound, Alaska. Sci Total Environ 398:20–25

Burger J, Tsipoura N, Newhouse M, Jeitner C, Gochfeld M, Mizrahi D (2011) Lead, mercury, cadmium, chromium, and arsenic levels in eggs, feathers, and tissues of Canada geese of the New Jersey meadowlands. Environ Res 111:775–784

Bustamante P, Bocher P, Cherel Y, Miramand P, Caurant F (2003) Distribution of trace elements in the tissues of benthic and pelagic fish from the Kerguelen Islands. Sci Total Environ 313:25–39

Byrns MC, Penning TM (2011) Environmental toxicology. Carcinogens and heavy metals. In: Brunton L, Chabner B, Knollman B (eds) The pharmacological basis of therapeutics. McGraw Hill, New York, pp 1853–1878

Calle P, Alvarado O, Monserrate L, Cevallos JM, Calle N, Alava JJ (2015) Mercury accumulation in sediments and seabird feathers from the Antarctic peninsula. Mar Pollut Bull 91:410–417

Campbell LM, Norstrom RJ, Hobson KA, Muir D, Backus S, Fisk AT (2005) Mercury and other trace elements in a pelagic Arctic marine food web (Northwater polynya, Baffin Bay). Sci Total Environ 351-352:247–263

Carlini AR, Coria NR, Santos MM, Negrete J, Juares MA, Daneri GA (2009) Responses of *Pygoscelis adeliae* and *P. papua* populations to environmental changes at Isla 25 de Mayo (king George Island). Polar Biol 32:1427–1433

Carravieri A, Bustamante P, Churlaud C, Cherel Y (2013) Penguins as bioindicators of mercury contamination in the Southern Ocean: birds from the Kerguelen Islands as a case study. Sci Total Environ 454-455:141–148

Carravieri A, Bustamante P, Churlaud C, Fromant A, Cherel Y (2014) Moulting patterns drive within-individual variations of stable isotopes and mercury in seabird body feathers: implications for monitoring of the marine environment. Mar Biol 161:963–968

Carravieri A, Cherel Y, Jaeger A, Churlaud C (2016) Penguins as bioindicators of mercury contamination in the southern Indian Ocean: geographical and temporal tends. Environ Pollut 213:195–205

Casini S, Fossi M, Gavilan J, Barra R, Parra O, Leonzio C, Focardi S (2001) Porphyrin levels in excreta of seabirds of the Chilean coasts as nondestructive biomarker of exposure to environmental pollutants. Arch Environ Contam Toxicol 4:65–72

Casini S, Fossi M, Leonzio C, Renzoni A (2003) Review: porphyrins as biomarkers for hazard assessment of bird populations: destructive and non-destructive use. Ecotoxicology 12:297–305

Celis J, Jara S, González-Acuña D, Barra R, Espejo W (2012) A preliminary study of trace metals and porphyrins in excreta of gentoo penguins (*Pygoscelis papua*) at two locations of the Antarctic peninsula. Arch Med Vet 44:311–316

Celis JE, Espejo W, González-Acuña D, Jara S, Barra R (2014) Assessment of trace metals and porphyrins in excreta of Humboldt penguins (*Spheniscus humboldti*) in different locations of the northern coast of Chile. Environ Monit Assess 186:1815–1824

Celis JE, Espejo W, Barra R, Gonzalez-Acuña D, Gonzalez F, Jara S (2015a) Assessment of trace metals in droppings of Adélie penguins (*Pygoscelis adeliae*) from different locations of the Antarctic peninsula area. Adv Polar Sci 26:1–7

Celis JE, Barra R, Espejo W, González-Acuña D, Jara S (2015b) Trace element concentrations in biotic matrices of gentoo penguins (*Pygoscelis papua*) and coastal soils from different locations of the Antarctic peninsula. Water Air Soil Pollut 226:1–12

Chen CY, Serrell N, Evers DC, Fleishman BJ, Lambert KF, Weiss J, Mason RP, Bank MS (2008) Meeting report: methylmercury in marine ecosystems—from sources to seafood consumers. Environ Health Perspect 116:1706–1712

Cifuentes JM, Becker PH, Sommer U, Pacheco P, Schlatter R (2003) Seabird eggs as bioindicators of chemical contamination in Chile. Environ Pollut 126:123–137

Clarke KR, Somerfield PJ, Chapman MG (2006) On resemblance measures for ecological studies, including taxonomic dissimilarities and a zero-adjusted bray–Curtis coefficient for denuded assemblages. J Exp Mar Biol Ecol 330:55–80

Cooper J, Crawford RJM, De Villiers M, Dyer BM, Hofmeyr GJG, Jonker A (2009) Disease outbreaks among penguins at sub-Antarctic Marion Island: a conservation concern. Mar Ornithol 37:193–196

Croxall JP, Prince PA, Reid K (1997) Dietary segregation of krill eating South Georgia seabirds. J Zool 242:531–556

Custer T, Custer C, Eichhorst B, Warburton D (2007) Selenium and metal concentrations in waterbird eggs and chicks at Agassiz National Wildlife Refuge, Minnesota. Arch Environ Contam Toxicol 53:103–109

Daso AP, Okonkwo JO, Jansen R, Brandao JD, Kotzé A (2015) Mercury concentrations in eggshells of the southern ground-hornbill (*Bucorvus leadbeateri*) and Wattled crane (*Bugeranus carunculatus*) in South Africa. Ecotoxicol Environ Saf 114:61–66

Dauwe T, Bervoets L, Blust R, Pinxten R, Eens M (2000) Can excrement and feathers of nestling songbirds be used as biomonitors for heavy metal pollution? Arch Environ Contam Toxicol 39:541–546

Dauwe T, Janssens E, Bervoets L, Blust R, Eens M (2005) Heavy-metal concentrations in female laying great tits (*Parus major*) and their clutches. Arch Environ Contam Toxicol 49:249–256

De Matos R (2008) Calcium metabolism in birds. Vet Clin Exot Anim 11:59–82

De Matteis F, Lim CK (1994) Porphyrins as nondestructive indicators of exposure to environmental pollutants. In: Fossi MC, Leoncio C (eds) Nondestructive biomarkers in vertebrates. Lewis, Boca Raton, FL, pp 93–128

De Moreno JEA, Gerpe MS, Moreno VJ, Vodopivez C (1997) Heavy metals in Antarctic organisms. Polar Biol 17:131–140

Debacker V, Jauniaux T, Coignoul F, Bouquegneau JM (2000) Heavy metals contamination and body condition of wintering guillemots (Uria Aalge) at the Belgian coast from 1993 to 1998. Environ Res 84(3):310–317

Deheyn DD, Gendreau P, Baldwin RJ, Latz MI (2005) Evidence for enhanced bioavailability of trace elements in the marine ecosystem of Deception Island, a volcano in Antarctica. Mar Environ Res 60:1–33

Dehn L, Follmann E, Thomas D, Sheffield G, Rosa C, Duffy L, O'Hara T (2006) Trophic relationships in an Arctic food web and implications for trace metal transfer. Sci Total Environ 362:103–123

Del Hoyo J, Elliott A, Sargatal J (1992) Handbook of the birds of the world. Volume 1: ostrich to ducks. Lynx Edicions. Barcelona, Spain, p 696

Dos Santos IR, Silva-Filho EV, Schaefer CE, Albuquerque-Filho MR, Campos LS (2005) Heavy metal contamination in coastal sediments and soils near the Brazilian Antarctic Station, king George Island. Mar Pollut Bull 50:185–194

Eisler R (1985) Selenium hazards to fish, wildlife and invertebrates. A synoptic review. U.S. Fish and Wildlife Service, Washington DC. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=7297. Accessed 31 May 2016

Eisler R (1987) Mercury hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and WildlifeService, Washington DC. https://www.pwrc.usgs.gov/eisler/CHR_10_Mercury.pdf

Eisler R (1988) Lead hazards to fish, wildlife, and invertebrates. A synoptic review. U.S. Fish and Wildlife Service, Washington DC. https://www.pwrc.usgs.gov/eisler/CHR_14_Lead.pdf. Accessed 31 May 2016

Eisler R (1993) Zinc hazards to fish, wildlife and invertebrates. A synoptic review. U.S. Fish and Wildlife Service, Washington DC. https://www.pwrc.usgs.gov/eisler/CHR_26_Zinc.pdf. Accessed 31 May 2016

Eisler R (1998) Copper hazards to fish, wildlife, and invertebrates. A synoptic review. U.S. Fish and Wildlife Service, Washington DC. https://www.pwrc.usgs.gov/eisler/CHR_33_Copper.pdf. Accessed 31 May 2016

Elliot JE, Scheuhammer AM, Leighton FA, Pearce PA (1992) Heavy metal and metallothionein concentrations in Atlantic Canadian seabirds. Arch Environ Contam Toxicol 22:63–73

Erikson KM, Aschner M (2003) Manganese neurotoxicity and glutamate-GABA interaction. Neurochem Int 43:475–480

Espejo W, Celis J, González-Acuña D, Jara S, Barra R (2014) Concentration of trace metals in excrements of two species of penguins from different locations of the Antarctic peninsula. Polar Biol 37:675–683

Evers DC, Savoy LJ, DeSorbo CR, Yates DE, Hanson W, Taylor KM, Siegel LS, Cooley JH Jr, Bank MS, Major A, Munney K, Mower BF, Vogel HS, Schoch N, Pokras M, Goodale MW, Fair J (2008) Adverse effects from environmental mercury loads on breeding common loons. Ecotoxicology 17:69–81

Falkowska L, Reindl AR, Szumilo E, Kwaśniak J, Staniszewska M, Bełdowska M, Lewandowska A, Krause I (2013) Mercury and chlorinated pesticides on the highest level of the food web as exemplified by herring from the southern Baltic and African penguins from the zoo. Water Air Soil Pollut 224:1549

Fimreite N (1974) Mercury contamination of aquatic birds in northwestern Ontario. J Wildl Manag 38:120–131

Finger A, Lavers JL, Dann P, Nugegoda D, Orbell JD, Robertson B, Scarpaci C (2015) The little penguin (*Eudyptula minor*) as an indicator of coastal trace metal pollution. Environ Pollut 205:365–377

Fitzgerald WF, Lamborg CH, Hammerschmidt CR (2007) Marine biogeochemical cycling of mercury. Chem Rev 107:641–662

Franson JC (1996) Interpretation of tissue lead residues in birds other than waterfowl. In: Beyer WN, Heinz GH, Redmon-Norwood AW (eds) Environmental contaminants in wildlife. Interpreting tissue concentrations. Lewis, Boca Raton, FL, pp 264–279

Franson JC, Hollmén TE, Flint PL, Grand JB, Lanctot RB (2003) Contaminants in molting long-tailed ducks and nesting common eiders in the Beaufort Sea. Mar Pollut Bull 45:504–513

Franson JC, Hoffman DJ, Wells-Berlin A, Perry MC, Shearn-Bochsler V, Finley DL, Flint PL, Hollmén T (2007) Effects of dietary selenium on tissue concentrations, pathology, oxidative stress, and immune function in common eiders (*Somateria mollissima*). J Toxicol Environ Health A 70:861–874

Frias JE, Gil MN, Esteves JL, Borboroglu PG, Kane OJ, Smith JR, Boersma PD (2012) Mercury levels in feathers of Magellanic penguins. Mar Pollut Bull 64:1265–1269

Furness RW (1996) Cadmium in birds. In: Beyer WN, Heinz GH, Redmon-Norwood AW (eds) Environmental contaminants in wildlife. Interpreting tissue concentrations. Lewis, Boca Raton, FL, pp 389–404

Furness RW, Muirhead SJ, Woodburn M (1986) Using bird feathers to measure mercury in the environment: relationships between mercury content and molt. Mar Pollut Bull 17:27–30

García P, Boersma PD (2013) Penguins: natural history and conservation. University of Washington Press, Seattle & London, p 328

Gasparik J, Vladarova D, Capcarova M, Smehyl P, Slamecka J, Garaj P, Stawarz R, Massanyi P (2010) Concentration of lead, cadmium, mercury and arsenic in leg skeletal muscles of three species of wild birds. J Environ Sci Health A 45:818–823

Gibbs PJ (1995) Heavy metal and organochlorine concentrations in tissues of the little penguin *Eudyptula minor*. In: Dann P, Norman I, Reilly P (eds) The penguins. Surrey Beatty & Sons, Australia, pp 393–419

Gilani SH, Alibhai Y (1990) Teratogenicity of metals to chick embryos. Toxicol Environ Health 30:23–31

Gochfeld M (1997) Spatial patterns in a bioindicator: heavy metal and selenium concentration in eggs of herring gulls (*Larus argentatus*) in the New York bight. Arch Environ Contam Toxicol 33:63–70

Gochfeld M, Belant JL, Shukla T, Benson T, Burger J (1996) Heavy metals in laughing gulls: gender, age and tissue differences. Environ Toxicol Chem 15:2275–2283

Goutner V, Furness R, Papakonstantinou K (2000) Mercury in feathers of Audouin's Gull (*Larus audouinii*) chicks from northeastern Mediterranean colonies. Arch Environ Contam Toxicol 39:200–204

Goutte A, Barbraud C, Herzke D, Bustamante P, Angelier F, Tartu S, Clément-Chastel C, Moe B, Bech C, Gabrielsen GW, Bustnes JO, Chastel O (2015) Survival rate and breeding outputs in a high Arctic seabird exposed to legacy persistent organic pollutants and mercury. Environ Pollut 200:1–9

Goyer RA (1997) Toxic and essential metal interactions. Annu Rev Nutr 17:37–50

Hoffman DJ (2002) Role of selenium toxicity and oxidative stress in aquatic birds. Aquat Toxicol 57:11–26

Honda K, Yamamoto Y, Hidaka H, Tatsukawa R (1986) Heavy metal accumulation in Adélie penguin, *Pygoscelis adeliae*, and their variations with the reproductive process. Mem Natl Inst Polar Res 40:443–453

Honda K, Marcovecchio JE, Kan S, Tatsukawa R, Ogi H (1990) Metal concentrations in pelagic seabirds from the North Pacific Ocean. Arch Environ Contam Toxicol 19:704–711

Iavicoli I, Fontana L, Bergamaschi A (2009) The effects of metals as endocrine disruptors. J Toxicol Environ Health B 12:206–223

Ikemoto T, Kunito T, Tanaka H, Baba N, Miyazaki N, Tanabe S (2004) Detoxification mechanism of heavy metals in marine mammals and seabirds: interaction of selenium with mercury, silver, copper, zinc, and cadmium in liver. Arch Environ Contam Toxicol 47:402–413

Jerez S, Motas M, Palacios MJ, Valera F, Cuervo JJ, Barbosa A (2011) Concentration of trace elements in feathers of three Antarctic penguins: geographical and interspecific differences. Environ Pollut 159:2412–2419

Jerez S, Motas M, Benzal J, Diaz J, Vidal V, D'Amico V, Barbosa A (2013a) Distribution of metals and trace elements in adult and juvenile penguins from the Antarctic peninsula area. Environ Sci Pollut R 20:3300–3311

Jerez S, Motas M, Benzal J, Diaz J, Barbosa A (2013b) Monitoring trace elements in Antarctic penguin chicks from south Shetland Islands, Antarctica. Mar Pollut Bull 69:67–75

Jin S, Seo S, Shin Y, Bing K, Kang T, Paek W, Lee D (2012) Heavy metal accumulations of 4 species of Anseriformes in Korea. J Korean Nat 5:345–349

Kaur N, Dhanju CK (2013) Heavy metals concentration in excreta of free living wild birds as indicator of environmental contamination. Bioscan 8:1089–1093

Kehrig HA, Hauser-Davis RA, Seixas TG, Fillmann G (2015) Trace-elements, methylmercury and metallothionein levels in Magellanic penguin (*Spheniscus magellanicus*) found stranded on the southern Brazilian coast. Mar Pollut Bull 96:450–455

Khan A, Hussain H, Sattar A, Khan M, Abbas R (2014) Toxico-pathological aspects of arsenic in birds and mammals: a review. Int J Agric Biol 16:1213–1224

Kim J, Koo T (2007) Heavy metal concentrations in diet and livers of black-crowned night heron *Nycticorax nycticorax* and grey heron *Ardea cinerea* chicks from Pyeongtaek, Korea. Ecotoxicology 16:411–416

Kim J, Oh J (2014a) Trace element concentrations in eggshells and egg contents of black-tailed gull (*Larus crassirostris*) from Korea. Ecotoxicology 23:1147–1152

Kim J, Oh J (2014b) Relationships of metals between feathers and diets of black-tailed gull (*Larus crassirostris*) chicks. Bull Environ Contam Toxicol 92:265–269

Kim J, Oh J (2014c) Heavy metal concentrations in black-tailed gull (*Larus crassirostris*) chicks, Korea. Chemosphere 112:370–376

Kim EY, Murakami T, Saeki K, Tatsukawa R (1996) Mercury levels and its chemical form in tissues and organs of seabirds. Arch Environ Contam Toxicol 30:259–266

Kim EY, Goto R, Tanabe S, Tanaka H, Tatsukawa R (1998) Distribution of 14 elements in tissues and organs of oceanic seabirds. Arch Environ Contam Toxicol 35:638–645

Kim M, Park K, Park J, Kwak I (2013) Heavy metal contamination and metallothionein mRNA in blood and feathers of black-tailed gulls (*Larus crassirostris*) from South Korea. Environ Monit Assess 185:2221–2230

Kler T, Vashishat N, Kumar M (2014) Heavy metals concentration in excreta of avian species from Ludhiana district. Int J Adv Res 2:873–879

Lalancette A, Morin Y, Measures L, Fournier M (2003) Contrasting changes of sensitivity by lymphocytes and neutrophils to mercury in developing grey seals. Dev Comp Immunol 27:735–747

Larison JR, Likens GE, Fitzpatrick JW, Crock JG (2000) Cadmium toxicity among wildlife in the Colorado Rocky Mountains. Nature 406:181–183

Lavoie R, Jardine T, Chumchal M, Kidd K, Campbell L (2013) Biomagnification of mercury in aquatic food webs: a worldwide meta-analysis. Environ Sci Technol 47:13385–13394

Lebedeva NV (1997) Accumulation of heavy metals by birds in the southwest of Russia. Russ J Ecol 28:41–46

Lee DP (1996) Relationship of heavy metal level in birds. Bull Kor Inst Orni 5:59–67

Lemley AD (1993) Guidelines for evaluating selenium data form aquatic monitoring and assessment studies. Environ Monit Assess 28:83–100

Lescroël A, Ridoux V, Bost CA (2004) Spatial and temporal variation in the diet of the gentoo penguin (*Pygoscelis papua*) at Kerguelen Islands. Polar Biol 27:206–216

Lim CK (1991) Porphyrins. In: Hanai T (ed) Liquid chromatography in biomedical analysis. Elsevier, Amsterdam, pp 209–229

Lock JW, Thompson DR, Furness RW (1992) Metal concentrations in seabirds of the New Zealand region. Environ Pollut 75:289–300

Lucia M, André JM, Gontier K, Diot N, Veiga J, Davail S (2010) Trace element concentrations (mercury, cadmium, copper, zinc, lead, aluminum, nickel, arsenic, and selenium) in some aquatic birds of the Southwest Atlantic Coast of France. Arch Environ Contam Toxicol 58:844–853

Majer A, Petti M, Corbisier T, Ribeiro A, Theophilo C, de Lima FP, Figueira R (2014) Bioaccumulation of potentially toxic trace elements in benthic organisms of Admiralty Bay (king George Island, Antarctica). Mar Pollut Bull 79:321–325

Malinga M, Szefer P, Gabrielsen G (2010) Age, sex and spatial dependent variations in heavy metals levels in the glaucous gulls (*Larus hyperboreus*) from the Bjørnøya and Jan Mayen, Arctic. Environ Monit Assess 169:407–416

Mansouri B, Babaei H, Hoshyari E (2012) Heavy metal contamination in feathers of western reef heron (*Egretta gularis*) and Siberian gull (*Larus heuglini*) from hara biosphere reserve of southern Iran. Environ Monit Assess 184:6139–6145

Martinez-Haro M, Taggart M, Mateo R (2010) Pb-al relationships in waterfowl feces discriminate between sources of Pb exposure. Environ Pollut 158:2485–2489

Mateo R, Lacorte S, Taggart M (2016) An overview of recent trends in wildlife ecotoxicology. Curr Trends Wildlife Res 1:125–150

Mathews T, Fisher N (2008) Trophic transfer of seven trace metals in a four-step marine food chain. Mar Ecol Prog Ser 367:23–33

Metcheva R, Yurukova L, Teodorova S, Nikolova E (2006) The penguin feathers as bioindicator of Antarctica environmental state. Sci Total Environ 362:259–265

Metcheva R, Yurukova L, Bezrukov V, Beltcheva M, Yankov Y, Dimitrov K (2010) Trace and toxic elements accumulation in food chain representatives at Livingston Island (Antarctica). Int J biol 2:155

Metcheva R, Yurukova L, Teodorova SE (2011) Biogenic and toxic elements in feathers, eggs, and excreta of gentoo penguin (*Pygoscelis papua ellsworthii*) in the Antarctic. Environ Monit Assess 182:571–585

Monteiro LR, Furness RW (2001) Kinetics, dose-response, and excretion of methylmercury in free-living adult Cory's shearwaters. Environ Sci Technol 35:739–746

Morera M, Sanpera C, Crespo S, Jover L, Ruiz X (1997) Inter- and intraclutch variability in heavy metals and selenium levels in Audouin's gull eggs from the Ebro Delta, Spain. Arch Environ Contam Toxicol 33:71–75

Nayak P (2002) Aluminum: impacts and disease. Environ Res 89:101–115

Neff JM (1997) Ecotoxicology of arsenic in the marine environment. Environ Toxicol Chem 16:917–927

Newman MC (2015) Fundamentals of ecotoxicology: the science of pollution. CRC Press, Boca Raton, FL, p 680

Nordberg M, Nordberg GF (2016) Trace element research-historical and future aspects. J Trace Elem Med Biol 38:46–52

Norheim G, Borch-Iohnsen B (1990) Chemical and morphological studies of liver from eider (*Somateria mollissima*) in Svalbard with special reference to the distribution of copper. J Comp Pathol 102:457–466

Nygard T, Lie E, Rov N, Steinnes E (2001) Metal dynamics in an Antarctic food chain. Mar Pollut Bull 42:598–602

Nyholm NE (1981) Evidence of involvement of aluminum in causation of defective formation of eggshells and of impaired breeding in wild passerine birds. Environ Res 26:363–371

O'Flaherty EJ (1998) Physiologically based models of metal kinetics. Crit Rev Toxicol 28:271–317

Ochoa-Acuña H, Sepúlveda MS, Gross TS (2002) Mercury in feathers from Chilean birds: influence of location: feeding strategy, and taxonomic affiliation. Mar Pollut Bull 44:340–345

Ohlendorf HM, Kilness AW, Simmons JL, Stroud RK, Hoffman DJ, Moore JF (1988) Selenium toxicosis in wild aquatic birds. Toxicol Environ Health 24:67–92

Orłowski G, Polechoński R, Dobicki W, Zawada Z (2007) Heavy metal concentrations in the tissues of the black-headed gull *Larus ridibundus* L. nesting in the dam reservoir in south-western Poland. Pol J Ecol 55:777–787

Outridge PM, Scheuhammer AM (1993) Bioaccumulation and toxicology of chromium: implications for wildlife. Rev Environ Contam Toxicol 130:31–77

Parslow JLF, Jefferies DJ, Hanson HM (1973) Gannet mortality incidents in 1972. Mar Pollut Bull 4:41–43

Pedro S, Xavier JC, Tavares S, Trathan PN, Ratcliffe N, Paiva VH, Medeiros R, Pereira E, Pardal M (2015) Feathers as a tool to assess mercury contamination in gentoo penguins: variations at the individual level. PLoS One 10:e0137622. doi:10.1371/journal.pone.0137622

Pérez-López M, Cid-Galán F, Hernández-Moreno D, Oropesa-Jiménez AL, López-Beceiro A, Fidalgo-Álvarez LE, Soler-Rodríguez F (2005) Contenido de metales pesados en hígado y plumas de aves marinas afectadas por el accidente del "Prestige" en la costa de Galicia. Rev Toxicol 22:191–199. (in Spanish)

Prashanth L, Kattapagari KK, Chitturi RT, Baddam VR, Prasad LK (2016) A review on role of essential trace elements in health and disease. J NTR Univ Health Sci 4:75–85

Raidal SR, Shearer PL, Cannell BL, RJDB N (2006) Micromelia in little penguins (*Eudyptula minor*). J Avian Med Surg 20:258–262

Rattner BA, Golden NH, Toschik PC, McGowan PC, Custer TW (2008) Concentrations of metals in blood and feathers of nestling ospreys (*Pandion haliaetus*) in Chesapeake and Delaware bays. Arch Environ Contam Toxicol 54:114–122

Ribeiro AR, Eira C, Torres J, Mendes P, Miquel J, Soares AMVM, Vingada J (2009) Toxic element concentrations in the razorbill *Alca torda* (Charadriiformes, Alcidae) in Portugal. Arch Environ Contam Toxicol 56:588–595

Rodrigue J, Champoux L, Leclair D, Duchesne JF (2007) Cadmium concentrations in tissues of willow ptarmigan (*Lagopus lagopus*) and rock ptarmigan (*Lagopus muta*) in Nunavik, northern Québec. Environ Pollut 147:642–647

Roth JA (2006) Homeostatic and toxic mechanisms regulating manganese uptake, retention, and elimination. Biol Res 39:45–57

Rothschild RFN, Duffy LK (2005) Mercury concentrations in muscle, brain and bone of western Alaskan waterfowl. Sci Total Environ 349:277–283

Sagerup K, Savinov V, Savinova T, Kuklin V, Muir D, Gabrielsen G (2009) Persistent organic pollutants, heavy metals and parasites in the glaucous gull (*Larus hyperboreus*) on Spitsbergen. Environ Pollut 157:2282–2290

Sanchez-Hernandez JC (2000) Trace element contamination in Antarctic ecosystems. Rev Environ Toxicol 166:83–127

Sánchez-Virosta P, Espína S, García-Fernández AJ, Eeva T (2015) A review on exposure and effects of arsenic in passerine birds. Sci Total Environ 512-513:506–525

Santos IR, Silva-Filho EV, Schaefer C, Maria S, Silva CA, Gomes V, Passos MJ, Van Ngan P (2006) Baseline mercury and zinc concentrations in terrestrial and coastal organisms of Admiralty Bay, Antarctica. Environ Pollut 140:304–311

Šaric M, Lucchini R (2007) Manganese. In: Nordberg GF, Fowler BA, Nordberg M, Friberg L (eds) Handbook on the toxicology of metals. Academic Press, London, pp 645–674

Savinov VM, Gabrielsen GW, Savinova TN (2003) Cadmium, zinc, copper, arsenic, selenium and mercury in seabirds from the Barents Sea: levels, inter-specific and geographical differences. Sci Total Environ 306:133–158

Scheifler R, Gauthier-Clerc M, Bohec CL, Crini N, Cœurdassier M, Badot PM, Giraudoux P, Maho YL (2005) Mercury concentrations in king penguin (*Aptenodytes patagonicus*) feathers at Crozet Islands (sub-Antarctic): temporal trend between 1966–1974 and 2000–2001. Environ Toxicol Chem 24:125–128

Scheuhammer AM (1987) The chronic toxicity aluminium, cadmium, mercury and lead in birds: a review. Environ Pollut 46:263–295

Scheuhammer AM, Basu N, Burgess NM, Elliot JE, Campbell GD, Wayland M, Champoux L, Rodrigue J (2008) Relationships among mercury, selenium, and neurochemical parameters in common loons (*Gavia immer*) and bald eagles (*Haliaeetus leucocephalus*). Ecotoxicology 17:93–101

Sjögren B, Iregren A, Elinder C-G, Yokel RA (2007) Aluminum. In: Nordberg GF, Fowler BA, Nordberg M, Friberg L (eds) Handbook on the toxicology of metals. Academic Press, London, pp 339–352

Skoric S, Visnjić-Jeftic Z, Jaric I, Djikanovic V, Mickovic B, Nikcevic M, Lenhardt M (2012) Accumulation of 20 elements in great cormorant (*Phalacrocorax carbo*) and its main prey, common carp (*Cyprinus carpio*) and Prussian carp (*Carassius gibelio*). Ecotoxicol Environ Saf 80:244–251

Smichowski P, Vodopivez C, Muñoz-Olivas R, Gutierrez AM (2006) Monitoring trace elements in selected organs of Antarctic penguin (*Pygoscelis adeliae*) by plasma-based techniques. Microchem J 82:1–7

Soria ML, Repetto G, Repetto M (1995) Revisión general de la toxicología de los metales. In: Repetto M (ed) Toxicología avanzada. Ediciones Díaz de Santos, Madrid, pp 293–358 (in Spanish)

Sparling DW, Lowe TP (1996) Environmental hazards of aluminum to plants, invertebrates, fish, and wildlife. Rev Environ Contam Toxicol 145:1–127

Steinhagen-Schneider G (1986) Cadmium and copper levels in seals, penguins and skuas from the Weddell Sea in 1982/1983. Polar Biol 5:139–143

Stewart FM, Phillips RA, Catry P, Furness RW (1997) Influence of species, age and diet on mercury concentrations in Shetland seabirds. Mar Ecol-Prog Ser 151:237–244

Suedel BC, Boraczek JA, Peddicord RK, Clifford PA, Dillon TM (1994) Trophic transfer and biomagnification potential of contaminants in aquatic ecosystems. Rev Environ Contam Toxicol 136:21–89

Sun L, Xie Z (2001) Changes in lead concentration in Antarctic penguin droppings during the past 3,000 years. Environ Geol 40:1205–1208

Szefer P, Pempkowiak J, Skwarzec B, Bojanowski R, Holm E (1993) Concentration of selected metals in penguins and other representative fauna of the Antarctica. Sci Total Environ 138:281–288

Szopińska M, Namieśnik J, Polkowska Z (2016) How important is research on pollution levels in Antarctica? Historical approach, difficulties and current trends. Rev Environ Contam Toxicol. doi: 10.1007/398_2015_5008

Tartu S, Goutte A, Bustamante P, Angelier F, Moe B, Clément-Chastel C, Bech C, Gabrielsen GW, Bustnes JO, Chastel O (2013) To breed or not to breed: endocrine response to mercury contamination by an Arctic seabird. Biol Lett 9:20130317. doi:10.1098/rsbl.2013.0317

Tartu S, Bustamante P, Angelier F, Lendvai AZ, Moe B, Blévin P, Bech C, Gabrielsen GW, Bustnes JO, Chastel O (2016) Mercury exposure, stress and prolactin secretion in an Arctic seabird: an experimental study. Funct Ecol 30:596–604

Thompson DR (1990) Metal levels in marine vertebrates. In: Furness RW, Rainbow PS (eds) Heavy metals in the marine environment. CRC, Boca Raton, FL, pp 143–182

Tin T, Fleming Z, Hughes K, Ainley D, Convey P, Moreno C, Pfeiffer S, Scott J, Snape I (2009) Impacts of local human activities on the Antarctic environment. Antarct Sci 21:3–33

UICN (2016) The IUCN Red List of Thereatened Species 2014.3. http://www.iucnredlist.org/details/22697817/0. Accessed 2 Jan 2016

Wastney ME, House WA, Barnes RM, Subramanian KN (2000) Kinetics of zinc metabolism: variation with diet, genetics and disease. J Nutr 130:1355–1359

Williams TD (1990) Annual variation in breeding biology of gentoo penguin, *Pygoscelis papua*, at Bird Island, South Georgia. J Zool 222:247–258

Yin X, Xia L, Sun L, Luo H, Wang Y (2008) Animal excrement: a potential biomonitor of heavy metal contamination in the marine environment. Sci Total Environ 399:179–185

Zamani-Ahmadmahmoodi R, Alahverdi M, Mirzaei R (2014) Mercury concentrations in common tern *Sterna hirundo* and slender-billed gull *Larus genei* from the Shadegan marshes of Iran, in north-western corner of the Persian Gulf. Biol Trace Elem Res 159:161–166

Zhang W, Ma J (2011) Waterbirds as bioindicators of wetland heavy metal pollution. Procedia Environ Sci 10:2769–2774