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SHORT NOTE

The highest mercury concentrations ever reported in a South American bird, the Striated Caracara (*Phalcoboenus australis*)

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Abstract
Mercury is a widely available pollutant associated with negative effects on wildlife, especially top predators. Here, we characterized the mercury concentrations in feathers of Striated Caracara *Phalcoboenus australis* on Isla de los Estados (Argentina). With feather mercury levels averaging 26.3 mg/kg, this population has the highest mean feather mercury ever reported for a bird population in South America. We propose that the high mercury concentrations are related to the feeding habits of the species: during feather moult, they are strongly associated with a Southern Rockhopper Penguin (*Eudyptes chrysocome*) colony known to be highly exposed to mercury contamination. Our results suggest that this Striated Caracara population should be monitored for acute effects and potential impacts of mercury toxicity.

Keywords Hg · Exposure · Raptor · Conservation · Biomagnification · Heavy metals

Introduction

Mercury (Hg) is a widely available pollutant documented to have significant adverse effects on wildlife. Direct and acute effects of mercury exposure vary widely amongst species, including mortality, aberrant behaviours, reduced immune response and reproductive impairment (Scheuhammer 1987; Scheuhammer et al. 2007; Seewagen 2010). Birds of prey are at an elevated risk of exposure to toxic concentrations of mercury as they are long-lived predators foraging at high trophic levels (Berg et al. 1966; Becker 2003; Lourenço et al. 2011; Cristol et al. 2012).

The Striated Caracara (*Phalcoboenus australis*, hereafter caracara) is a near threatened raptor with a restricted distribution on islands off the coast of southern South America and in the Malvinas/Falklands islands (Ferguson-Lees and Christie 2001; IUCN 2019). During the breeding season, their diet consists mainly of eggs, chicks and carrion of seabirds and sealions (Strange 1996). As top predators and facultative scavengers, caracaras may be highly exposed to mercury accumulation. In particular, the resident population in Franklin Bay (Isla de los Estados) build their nests in close association with Southern Rockhopper penguins (*Eudyptes chrysocome*, hereafter rockhopper) and are the main predator of their eggs and chicks (Liljesthröm et al. 2008; Balza et al. 2017). Moreover, caracaras of all ages and breeding status depend on marine resources and particularly on penguin subsidies during breeding season (Balza et al. 2020). Rockhoppers breeding on Franklin Bay show feather mercury concentrations amongst the highest ever reported in penguins (5.10 ± 1.46 mg/kg, Brasso et al. 2015). The rockhopper penguin population in Isla de los Estados is the only South American penguin population known to exceed the documented lowest adverse effects levels based on adult feathers (5–40 mg/kg; see Ropert-Coudert et al. 2019). In this study, we provide the first report on mercury exposure

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of caracaras. We predict that the caracaras will be exposed to high levels of mercury contamination, and if this is a chronic process, chicks should be less contaminated than adults as they only have ~ 3 months of exposure when they complete their first set of feathers.

Methods

Fieldwork was conducted in Franklin Bay, a ~ 4 km^2 bay on Isla de los Estados (Tierra del Fuego, Argentina, 54°85′30 S, 64°83′90 W). During December 2016 and May 2017, moulted wing (n = 26) and tail (n = 10) feathers were collected during systematic occupancy surveys of caracara territories (for details see Balza et al. 2017). These samples included wing feathers from three birds found dead during the surveys. We also plucked two back feathers from captured birds (n = 10). We classified feathers as from adults (> 5 years old) or first-year juveniles (less than one year old and therefore reflecting mercury burden during chick rearing; Henny and Elliot 2007) following Strange (1996). Nine adult feathers were collected in nest sites (one feather/site), representing ~ 53% of the active nests in the 2016/2017 breeding season. The remaining samples represented ~ 10% of the total estimated population (n = 37 samples from 220 to 530 individuals, UB unpublished data). We therefore assume that they are independent samples.

As feather moult is the primary mechanism through which birds can excrete mercury (e.g. Renedo et al. 2021), recently moulted feathers can provide insights into mercury exposure in the previous year. Annual moult occurs during the spring and summer (September to March) in this population (UB, NAL and ARR unpublished). Therefore, the mercury signal in moulted feathers would represent accumulation since the previous moult with higher influence of recent dietary exposure during the period of feather growth (Bearhop et al. 2000; Bond and Diamond 2009), which in our case would correspond to when rockhopper penguins are present at the colony.

Feathers were cleaned in a series of deionized water and acetone baths to remove any exogenously deposited contaminants, air dried at room temperature for 24–48 h and stored in sealed plastic centrifuge tubes until analysed. A central part of the feather vane (in moulted feathers) or three whole back feathers (in captured birds) from each individual were cut into fine pieces using a pair of sterilized stainless-steel scissors to create a homogenous mixture. We subsampled ~ 10 g of feathers of each individual to analyse for total mercury using a Nippon MA-3000 Direct Mercury Analyzer at Weber State University (Ogden, UT, USA). Each set of 20 samples analysed was preceded and followed by two samples of a standard reference material (TORT-3, National Resource Council Canada). Mean percent recovery for the standard reference material was 98.5% (n = 8) with relative significant differences in mercury concentration of 2.6%. Mercury concentrations in feathers are reported as mg/kg fresh weight.

Intra-individual variation has been found amongst feather types due to moulting sequence and timing (Dauwe et al. 2003; Cristol et al. 2012), but we were not able to design a sampling with more than one feather per individual. Therefore, to account for this possible effect, we modelled variation in mercury concentration as an additive function of both age and feather type. We use generalized linear models (GLM) with gamma error distribution and rank all possible models according to Akaike criterion corrected for small sample size (AICc) using MuMIn package in R software (Barton 2015; R Core Team 2018). Since only one best model was retained (see Results), we used the coefficients of the best model to estimate 95% confidence intervals for the mean value of mercury for each age group. We also used the coefficient of the null model to estimate 95% confidence intervals for the mean value of the whole population.

Results

We analysed 39 feather samples from adults and seven from juveniles. We detected mercury in all samples, and the average estimated mercury concentration for the whole population was 26.34 mg/kg (95% CI 22.11–31.72 mg/kg, range 0.79–85.46 mg/kg). Model selection using Akaike criterion retained the best model containing age as the only explanatory variable (Table 1), with more than two AICc values between it and the next model suggesting a single best model fit (Burnham and Anderson 2002). The best model explained 22% of the variability of mercury in feathers. Predicted mean values for Hg concentration in feathers were 29.19 mg/kg for adults (95% CI 24.86–35.35 mg/kg) and 10.47 mg/kg for juveniles (95% CI 7.42–17.79 mg/kg).

Table 1 Additive GLM models of mercury concentration in feathers of striated Caracara (*Phalcoboenus australis*) ranked by Akaike criterion corrected for small sample size (AICc)

Model	df	LogLik	AICc	Delta AICc	Weight
Age	3	− 183.95	374.5	0.0	0.90
Age+feather type	5	− 183.76	379.0	4.5	0.09
Null	2	− 189.98	384.2	9.7	0.01
Feather type	4	− 188.88	386.7	12.2	0.00

Columns represent degrees of freedom (df), logarithm of likelihood (LogLik), differences in AICc respect to the best model (Delta AICc) and the relative importance of each model (weight)

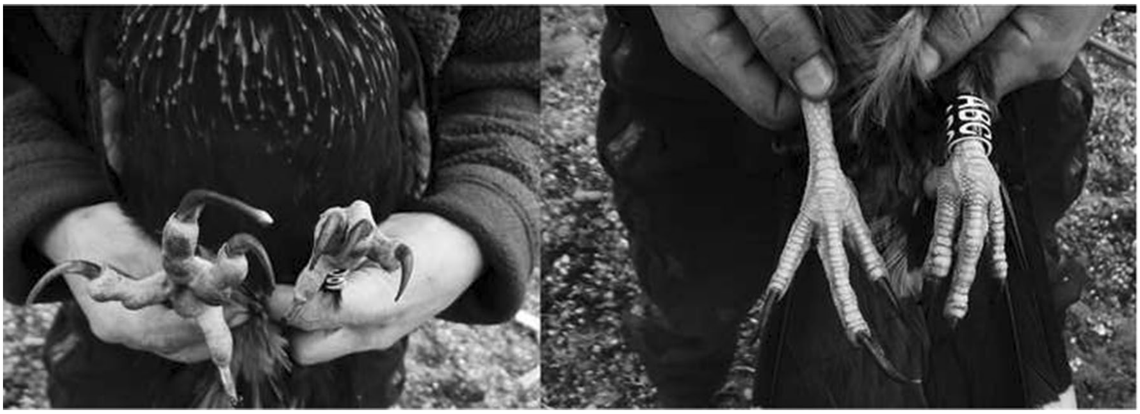

Fig. 1 A Striated Caracara (*Phalcoboenus australis*) adult female showing rigidity and overgrown claws in her right talon, with over 85 mg/kg feather mercury concentration

Discussion

This is the first report of mercury concentrations in Striated Caracaras and documents the highest mean values ever recorded for a bird population in South America. Overall, 96% of the samples in this study exceeded the documented 5 mg/kg lowest observable adverse effects threshold for bird feathers (Burger and Gochfeld 2000) and 17% were above 40 mg/kg (i.e. adverse effects documented in common loons, Evers et al. 2008). Raptor-specific adverse effects levels are unknown. Similar to other raptor studies, we found juveniles to have lower feather mercury concentrations than adults (Becker et al. 1994; Bowerman et al. 1994; Cahill et al. 1998; Carravieri et al. 2017). This could be explained by chronic exposure of adults that are at least five years old (Strange 1996). However, several other factors could be responsible for the unexplained variation in our model, including differences in physiology or foraging ecology between age groups (Balza et al. 2020).

The only suggestion of a potential effect that we found was that the bird with the highest mercury concentration in our study (85.46 mg/kg) was an adult female with overgrown talons and lack of motion in one of her claws (Fig. 1). Excretion of mercury through keratin production is a major pathway for decreasing the body burden of mercury in birds (Furness et al. 1986; Honda et al. 1986; Bearhop et al. 2000). It is possible that mercury eliminated into growing talons disrupted the availability of sulphur and/or cystine needed for keratin production leading to observable changes in the talon structure; however, we are not aware of evidence in the literature to support this pathway in birds. Feather mercury found in the present study exceeded concentrations reported in other caracara species in Brazil and northern Patagonia (Rapôso de Silva et al. 2017; Di Marzio et al. 2018).

Caracaras on Isla de los Estados feed on a restricted diet of mainly marine foragers (Balza et al. 2020), and their mercury concentrations were similar to those detected in other raptor species in North America commonly associated with aquatic prey (Bowerman et al. 1994; Hughes et al. 1997; Cahill et al. 1998; Bechard et al. 2009). Moreover, in the Southern Hemisphere, only marine top predators, like albatrosses, show similar mercury exposure (Carravieri et al. 2017; Cherel et al. 2018). We propose that at this site, rockhoppers serve as an environmental link importing marine pollutants to terrestrial food webs. If this is the case, not only would caracaras have elevated mercury reflecting previous patterns detected in sympatrically breeding rockhoppers, but their levels would be higher as a result of biomagnification. As a species of conservation concern, the high levels of mercury concentration reported in this study call for a long-term monitoring of this population of caracaras, including the possible implications on physiological and reproductive success.

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Author contributions UB, NAL and ARR conceived and designed research; UB and NAL conducted fieldwork; RB conducted mercury analysis; UB analysed data; UB wrote the first version of the manuscript; KP and ARR retrieved funds; all authors contributed with writing, discussion and editing various versions of the manuscript.

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Data availability Raw feather mercury data and scripts to reproduce the analysis in R can be found inhttps://github.com/ulisesbalza/Mercury_caracaras.

Declarations

Conflict of interest The authors declare no conflict of interest regarding this article.

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