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Morphometrics of the pink-footed shearwater (*Puffinus creatopus*): influence of sex and breeding site

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Abstract We present morphometric data for the pink-footed shearwater (*Puffinus creatopus*) from both Chilean breeding colonies on Isla Mocha and Juan Fernández: weight, total length, wing length, tail length, head length, three bill and three tarsus size measurements and length of middle toe. Significant differences were found for most measurements between males and females as well as between birds from the two different breeding localities. In general, males were bigger than females, and birds from Juan Fernández were bigger than those from Isla Mocha. Geographic differences most likely reflect some kind of ecomorphological adaptation. Some variables, especially the total length of head, seem to be useful for sex determination in the field.

Keywords Chile · Ecomorphology · *Puffinus carneipes* · *Puffinus creatopus* · Seabirds

Introduction

The pink-footed shearwater (*Puffinus creatopus*) is an endemic breeder in Chile. Its distribution is restricted to Isla Mocha (38°20'S, 73°55'W) and the Islas Santa Clara and Robinson Crusoe of the Juan Fernández archipelago (33°35'S, 78°55'W). The sites are almost

700 km from each other. Whereas Isla Mocha is situated only 35 km from the Chilean mainland, Juan Fernández is located offshore, about 620 km from the coast.

Estimated population sizes are 20,000–25,000 breeding pairs on Isla Mocha (Guicking 1999) and 4,000–4,500 breeding pairs on Juan Fernández (Brooke 1987; Guicking and Fielder 2000). Individual burrow counts on Juan Fernández in 2002 and 2003 returned even greater numbers for these islands (Hodum and Wainstein 2002, 2003). The pink-footed shearwater is considered globally threatened in the category “vulnerable” (BirdLife International 2000). During winter, it migrates along the Pacific coast of southern and central America to winter in the North Pacific. The pink-footed shearwater has recently been included in Appendix 1 of the Convention of Migratory Species.

The closest relative of the pink-footed shearwater is the flesh-footed shearwater (*Puffinus carneipes*), which breeds in New Zealand and Australia, and is also a transequatorial migrant wintering in the northern Pacific. The taxonomic status of the two is not yet completely determined. Both are considered as valid species at the moment. However, on the basis of coloration and skeleton, Palmer (1962) and Bourne (1983), for example, proposed them as subspecies.

Scientific research on the biology and ecology of the pink-footed shearwater is still at its very beginning. Morphometric measurements generally refer to birds caught in the northern Pacific and provide little information on the breeding origin of the birds.

Here we present the first morphometric data of the pink-footed shearwater that were collected in the two known breeding colonies of the species. Our data document intraspecific morphological differences, which might be useful for future field work (e.g., for sex determination), and may generate some ideas about ecological adaptations of birds from different breeding islands. Detailed knowledge of morphometric data might also be helpful to resolve taxonomic uncertainties.

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Methods

Field work was conducted in three successive breeding seasons during the nestling period, February-March 1998 and January-February 1999 on Isla Mocha (by D.G., C.L. and P.H.B.), and in February 2000 on the Islas Robinson Crusoe and Santa Clara, Juan Fernández archipelago (by D.G. and W.F.).

Birds were captured during the night, either by hand or with the help of nets that were spread in front of burrow entrances. All birds were ringed with rings of the ringing centre "Helgoland", Germany. Biometric measurements were taken from more than 100 birds on Isla Mocha and 27 birds on the Juan Fernández islands (6 on Isla Robinson Crusoe and 21 on Isla Santa Clara). The breeding status of most handled birds was unknown, but it seems likely that many birds were prospectors, as they did not occupy burrows.

The following biometric data were collected by the use of standard procedures (e.g. Spear and Ainley 1998; Genovart et al. 2003): body mass, total length (from tip of bill to tip of tail along the ventral surface of the moderately stretched bird; only measured from birds on Isla Mocha), wing length (from wrist of the folded wing to tip of the longest primary feather), tail length (tip of pygostyle to tip of central pair of tail feathers), total head length (hind head to tip of bill; head length as presented in Table 1 refers to that value after subtraction of bill length), bill length (from the border between rhamphoteca and prefrontal bone to tip of the bill), minimum bill height (measured at right angles to the course of the bill from upper edge of upper mandible to lower edge of lower mandible in the central part of the bill, where this measurement reaches a minimum), maximum bill height (analogous to minimum, the measurement reaches a maximum between the position of minimum bill height and proximal end of rhamphoteca), tarsus length (length of tarsometatarsus), tarsus height and width (stretch along the sagittal and transverse plane across the central part of tarsometatarsus) and length of middle toe (third digit from its inflection towards tarsometatarsus to the tip of the claw). Body mass was taken with an accuracy of 1 g (digital balance), head, bill, tarsus and middle toe lengths were measured with a calliper to 0.1 mm. For the other measurements we used a ruler and took the values with an accuracy of 0.5 mm.

Morphometric data were analysed by multivariate ANOVA and discriminant analysis, distinguishing between sexes and breeding localities (Isla Mocha vs Juan Fernández). To evaluate the observed differences in terms of possible morpho-ecological adaptations, all linear characters were standardised by dividing the measured value by the cube root of body mass (Spear and Ainley 1998).

Blood samples were taken from most birds for genetic analysis of sex. DNA was isolated from blood samples according to standard methods (Sambrook et al. 1989). PCR with sex specific primers published in Kahn et al. (1998) was performed, and PCR products were separated on high resolution polyacrylamide gels and visualised autoradiographically. Males are identified by one band and females by two bands, presumably reflecting different intron sizes in the CHD gene on the W versus the Z chromosome (Kahn et al. 1998).

Results

Morphometric measurements are summarised in Table 1. Males were in general bigger than females, and birds from Juan Fernández were generally bigger than those from Isla Mocha. These differences were significant for sex and breeding locality but not for the interaction of the two (two-factorial multivariate ANOVA: $F_{\text{sex}} = 13.24$, $P < 0.001$; $F_{\text{locality}} = 11.30$, $P < 0.001$; $F_{\text{interaction}} = 0.86$, $P = 0.586$). Significant influences of combined sex and locality were found for all variables with $P < 0.001$, only

for tarsus length and middle toe with $P < 0.01$ (two-factorial multivariate ANOVA). Results of the MANOVA for the standardised values of each variable are listed in the last column of Table 1. According to these comparisons, females had relatively longer tails than males and smaller bills. Birds from Juan Fernández had proportionally stouter bills, thicker legs and shorter tails than birds from Isla Mocha.

Discriminant analysis was able to separate all four groups of individuals (males from Isla Mocha, females from Isla Mocha, males from Juan Fernández and females from Juan Fernández; Fig. 1). The first two discriminant functions were capable of explaining 95.5 % of the observed variability (71.6 % and 23.9 %, respectively). Postanalytical classification ascribed 89.8 % of the cases to the right group (Table 2).

Bill and head measurements were most distinct between different classes. Total head length, measured from the hind head to the tip of the bill, appeared to be the most useful measurement for preliminary sex determination in the field, although not all birds would be classified unambiguously with this measurement (Fig. 2). Especially if the breeding locality is not known, correct determination of the sex might be problematic as males from Isla Mocha and females from Juan Fernández are quite alike in body size.

Discussion

Comparison of morphometrics of the pink-footed shearwater with those of its closest relative, the flesh-footed shearwater indicates that the former is slightly bigger (Palmer 1962). Slight differences between sexes with the males being bigger than the females are also reported for the flesh-footed shearwater (Marchant and Higgins 1990). These authors also mention some geographic variation for morphometric measurements of flesh-footed shearwaters, with birds from New Zealand being bigger than birds from western Australia, which indicates that birds of the *Puffinus carneipes/creatopus* complex are generally bigger further eastwards.

Geographic variation in morphometric measurements has been reported for several species of Procelariiformes, which in most cases is likely to reflect some adaptation to different environmental conditions. Spear and Ainley (1998) compared eight morphological characteristics among petrels of tropical versus southern polar regions. From this interspecific comparison they draw the conclusion that wind conditions, allocation and type of prey are driving factors for morphological variation in petrels. Larger bills, wings and tails are typical for the "tropical shearwaters" and enable birds to make use of relatively light winds when foraging over wide areas with rather sparse prey (Spear and Ainley 1998).

In the pink-footed shearwater, birds from the Juan Fernández Islands tend to be larger than birds from Isla Mocha with proportionally stouter bills and

Table 1 Morphometric measurements of male and female pink-footed shearwaters (*Puffinus creatopus*) at their two breeding colonies on Isla Mocha and Juan Fernández, as well as of males and females irrespective of the locality, and in total. For measurements of weight and length, sample sizes were a little smaller than indicated.

	Isla Mocha				Juan Fernández				Total	Statistical significance of standardised F -values ^a		
	♂		♀		♂		♀			Sex	Locality	Sex × locality
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range				
Sample size	37		25		14		13		38			
Weight (g)	Mean ± SD	733 ± 63.7	674 ± 64.7		781 ± 54.0	738 ± 34.4		51	749 ± 64.3	696 ± 63.4		146
Length (cm)	Range	628–865	576–776		677–879	660–788		628–879	576–788	576–889		723 ± 66.3
	Mean ± SD	47.3 ± 1.17	46.4 ± 1.12		–	–		47.3 ± 1.17	46.4 ± 1.12	47.0 ± 1.11		–
Wing length (cm)	Range	45.0–50.0	44.5–49.5		–	–		45.0–50.0	44.5–49.5	44.5–50.0		–
	Mean ± SD	33.4 ± 0.78	32.7 ± 0.73		33.9 ± 0.51	33.8 ± 6.1		33.5 ± 0.74	33.1 ± 0.86	33.3 ± 0.75	1.53 n.s.	0.51 n.s.
Tail length (cm)	Range	31.8–35.0	31.5–34.2		32.7–34.7	32.4–35.0		31.8–35.0	31.5–35.0	31.5–35.0		–
	Mean ± SD	11.3 ± 0.34	11.5 ± 0.41		11.0 ± 0.31	11.7 ± 0.32		11.2 ± 0.35	11.4 ± 0.39	11.4 ± 0.38	37.61 ***	8.50 **
Head length (mm)	Range	10.5–12.0	11.0–12.3		10.5–11.5	11.0–12.0		10.5–12.0	10.5–12.0	10.5–12.3		–
	Mean ± SD	58.1 ± 2.01	56.9 ± 2.06		58.4 ± 1.96	57.6 ± 1.85		58.2 ± 1.98	55.8 ± 1.39	57.0 ± 2.03	3.54 n.s.	2.26 n.s.
Bill length (mm)	Range	55.3–65.8	52.9–57.7		56.1–62.9	54.6–58.9		55.3–65.8	52.9–58.9	52.7–65.8		–
	Mean ± SD	43.6 ± 1.32	41.6 ± 1.45		44.4 ± 0.99	43.3 ± 1.69		43.8 ± 1.24	42.2 ± 1.73	42.9 ± 1.71	5.17 *	0.03 n.s.
Min. bill height (mm)	Range	41.4–46.5	38.6–44.2		42.5–45.7	40.9–46.6		41.4–46.5	38.6–46.6	38.6–46.6		–
	Mean ± SD	11.8 ± 0.53	11.2 ± 0.34		12.9 ± 0.56	12.1 ± 0.70		12.1 ± 0.72	11.5 ± 0.67	11.8 ± 0.73	6.70 *	32.91 ***
Max. bill height (mm)	Range	10.6–13.0	10.4–11.9		11.9–13.7	11.2–13.8		10.6–13.7	10.4–13.8	10.4–13.8		–
	Mean ± SD	17.2 ± 0.66	16.3 ± 0.56		18.0 ± 0.47	17.1 ± 0.43		17.4 ± 0.72	16.6 ± 0.63	17.0 ± 0.81	10.49 **	4.49 *
Tarsus length (mm)	Range	15.3–18.6	15.0–17.5		16.8–18.8	16.4–17.9		15.3–18.8	15.0–17.9	14.8–18.9		–
	Mean ± SD	56.0 ± 1.89	54.9 ± 3.24		57.5 ± 1.83	56.6 ± 1.29		56.4 ± 2.00	55.5 ± 2.82	56.0 ± 2.12	0.38 n.s.	0.06 n.s.
Tarsus height (mm)	Range	46.8–59.8	44.9–59.4		53.4–59.3	53.8–58.1		46.8–59.8	44.9–59.4	44.9–59.8		–
	Mean ± SD	6.7 ± 0.38	6.5 ± 0.44		7.5 ± 0.53	7.6 ± 0.40		6.9 ± 0.56	6.9 ± 0.67	7.0 ± 0.56	1.53 n.s.	47.40 ***
Tarsus width (mm)	Range	5.9–7.7	5.7–7.6		6.8–8.6	7.0–8.2		5.9–8.6	5.7–8.2	5.7–8.6		–
	Mean ± SD	4.4 ± 0.34	4.4 ± 0.32		4.8 ± 0.24	4.8 ± 0.18		4.5 ± 0.35	4.5 ± 0.32	4.5 ± 0.34	4.62 *	16.70 ***
Middle Toe (mm)	Range	3.9–5.8	4.0–5.3		4.4–5.2	4.4–5.1		3.9–5.8	4.0–5.3	3.8–5.8		–
	Mean ± SD	73.4 ± 2.84	71.4 ± 2.74		74.1 ± 2.40	74.6 ± 2.54		73.6 ± 2.73	72.5 ± 3.06	72.8 ± 3.04	1.47 n.s.	0.16 n.s.
Range		66.5–78.0	64.6–76.9		69.9–76.7	70.3–78.0		66.5–78.0	64.6–78.0	64.4–78.0		–

^a Sample sizes: sex: $n_{\text{female}} = 31$, $n_{\text{male}} = 39$; breeding locality: $n_{\text{Isla Mocha}} = 45$, $n_{\text{Juan Fernández}} = 25$

*** $P < 0.001$

** $P < 0.01$

* $P < 0.05$

n.s. not significant

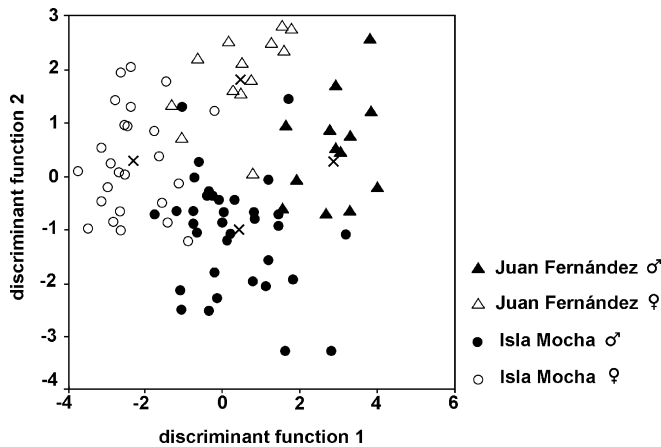


Fig. 1 Results of the discriminant analysis to distinguish between pink-footed shearwater (*Puffinus creatopus*) males from Isla Mocha, females from Isla Mocha, males from Juan Fernández and females from Juan Fernández. Each *symbol* represents one individual. *Crosses* represent group means

thicker legs but shorter tails. These differences might be the result of different environmental conditions at the two breeding localities and possibly different diets. Some evidence of different foraging areas exists from preliminary satellite tracking data. Whereas shearwaters from Isla Mocha fed relatively close to the island and along the Chilean coast (Guicking et al. 2001), the shearwaters from Juan Fernández fed out at sea (Hodum and Wainstein 2002, 2003). Prey availability is probably more variable offshore than along the Chilean coast.

It is noteworthy that our results give evidence that unlike most bird species the pink-footed shearwater does not conform to Bergmann's rule (Ashton 2002). This is another argument for the strong ecological divergence between the two islands, which is not simply explained by different latitude.

Several studies of petrels have found morphological (among others mainly size) differences between sexes: e.g. Solander's petrel (*Pterodroma solandri*) (Bester et al., submitted), Tahiti petrel (*Pterodroma rostrata*) (De Naurois and Erard 1979), and Great-winged

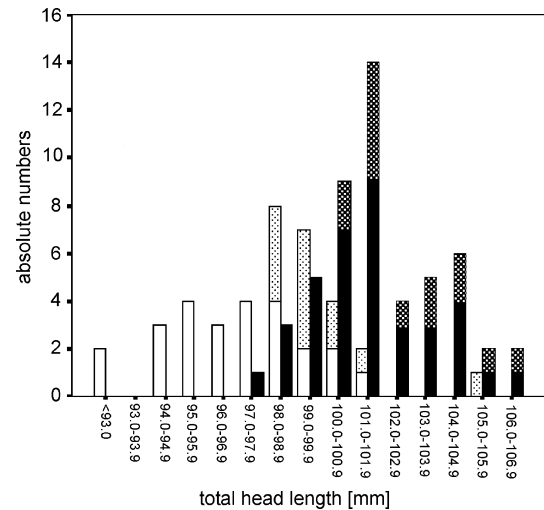


Fig. 2 Total lengths of head measured from the hind head to the tip of the bill for male and female pink-footed shearwaters. *Light bars* females, *dark bars* males; *solid bars* birds from Isla Mocha, *dotted bars* birds from Juan Fernández

petrel (*Pterodroma macroptera*) (Johnstone and Niven 1989). Sexual size dimorphism in giant petrel (*Macronectes giganteus*) could be linked to the different foraging strategies of the two sexes (González-Solís et al. 2000). However, interpretation of the observed size differences between sexes in the pink-footed shearwater is not yet possible as no detailed information on the feeding ecology of the species is available.

The question remains open whether the observed differences in morphology are reflected in genetic differentiation. Preliminary genetic analyses on intraspecific divergence of the pink-footed shearwater based on sequences of the mitochondrial cytochrome b gene and ISSR-PCR genomic fingerprints did not reveal island specific divergence (Guicking, unpublished data). However, differentiation between pink-footed and flesh-footed shearwaters with these markers was also very low, which suggests that more variable markers, e.g. microsatellites, would be more appropriate for studying intraspecific differentiation in this species.

Table 2 Postanalytical classification results of the discriminant analysis

Sex/locality			Prediction				Total
			Female / Isla Mocha	Male / Isla Mocha	Female / Juan Fernández	Male / Juan Fernández	
Original	Absolute numbers	female / Isla Mocha	23	1	1	0	25
		male / Isla Mocha	1	32	1	2	36
		female / Juan Fernández	2	1	10	0	13
		male / Juan Fernández	0	0	0	14	14
	%	female / Isla Mocha	92,0	4,0	4,0	0,0	100,0
		male / Isla Mocha	2,8	88,9	2,8	5,6	100,0
		female / Juan Fernández	15,4	7,7	76,9	0,0	100,0
		male / Juan Fernández	0,0	0,0	0,0	100,0	100,0

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