Using measurements to predict laying order in harvested Northern Rockhopper Penguin (*Eudyptes moseleyi*) eggs

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Abstract. The sustainable and responsible exploitation of natural populations for subsistence requires a scientific basis for management. Eggs of the Endangered Northern Rockhopper Penguin (*Eudyptes moseleyi*) in the Tristan da Cunha archipelago have been harvested since the 19th century with no restrictions on which (A- or B-eggs) can be harvested, despite the larger B-egg being much more likely to produce fledged offspring. Our objective was to create a discriminant function to predict the laying order of harvested eggs. We found that the discriminant function of $D = 0.58 \times Length + 0.39 \times Breadth -57.48$ successfully classified 91% of eggs as A- or B-eggs. When applied to previously collected harvest data, the discriminant function identified at least 36% of eggs as B-eggs. The method we describe here provides a mechanism around which one aspect of a management framework for the sustainable harvest of Northern Rockhopper Penguin eggs can be built.

Introduction

The sustainable and responsible exploitation of natural populations for subsistence requires a scientific basis for management and safety of harvesters, enforcement from management authorities and support from harvesters (Blanchard 1984; Elliot *et al.* 1991; Olsen and Nørrevang 2005; Merkel and Barry 2008). Many remote communities rely on subsistence harvests of a variety of marine vertebrates (Merkel and Barry 2008; Robards and Reeves 2011; Humber *et al.* 2014) and management authorities must ensure that such harvests are both sustainable and safe (Oka 1994; Lavers and Bond 2013; Jones *et al.* 2015).

Tristan da Cunha is an Overseas Territory of the United Kingdom in the South Atlantic Ocean comprised of four main islands and several offshore islets, which is home to ~270 residents in Edinburgh of the Seven Seas on the main island of Tristan. There is a long history of exploitation of wildlife for subsistence on the islands (Barrow 1910; Rogers 1927; Flint 1967; Wace and Holdgate 1976; Richardson 1984), although legislation now restricts this to Great Shearwater (*Ardenna gravis*) eggs and chicks and Northern Rockhopper Penguin (*Eudyptes moseleyi*) eggs (Government of St. Helena 2006). Historically, tens of thousands of penguin eggs were collected annually (Rogers 1927; Williams 1982; Richardson 1984),

resulting in a substantial reduction in the population on the main island of Tristan da Cunha. Since 1976, egg collecting has been largely confined to uninhabited Nightingale Island, and even here harvesting has decreased considerably in the 21st century (T. Glass, pers. obs.).

Crested Penguins (*Eudyptes* spp.) lay two eggs, the first of which (A-egg) is smaller than the second (B-egg) and rarely results in a fledged chick (Williams 1980; St. Clair and St. Clair 1996; Wilson *et al.* 2010; Stein and Williams 2013). Historically both eggs, or only the larger B-egg (the second-laid) were harvested, leading to concerns that such indiscriminate harvesting could impact penguin populations (Williams and Stone 1981). Although the current local legislation does not place restrictions on which eggs may be harvested (Government of St. Helena 2006), in recent years there has been increasing demand to harvest only the smaller A-egg, though this is not always adhered to and lacks a mechanism for enforcement. While A- and B-eggs are relatively easily identified at the nest site when they can be compared with each other, there is some size overlap, making the identification of the laying order of harvested eggs challenging (Williams 1995).

Northern Rockhopper Penguins are listed as Endangered by the IUCN (Birdlife International 2015), >80% of the global

population breeds on the islands of Tristan da Cunha, where they are declining (Cuthbert *et al.* 2009; Robson *et al.* 2011). The grounding of the MS *Oliva* in 2011, and subsequent oiling of a large number of penguins on Nightingale Island, Tristan da Cunha, combined with the species' precarious conservation status and more recent declines (A. L. Bond, T. Glass, unpubl. data) has resulted in a moratorium on egg harvesting since 2011.

Our objectives were to quantify the degree of dimorphism between A- and B-eggs, create a discriminant function to predict the laying order of harvested eggs and apply this function to a sample of harvested eggs measured in 1999 to estimate the number of A- and B-eggs. Doing so may provide a mechanism around which part of a management framework for the harvest of Northern Rockhopper Penguin eggs can be built.

Materials and methods

In September–October 2014, we measured 93 completed clutches on Nightingale Island (37°25'S, 12°28'W) and 43 completed clutches on Alex Island, 200 m offshore, classifying the larger of the two eggs as the B-egg, and the smaller the A-egg. We measured egg length and breadth using dial callipers to the nearest 0.1 mm. All measurements were taken by a single observer (GTWM) and measurement error, assessed by the repeated measuring of the same eggs was in the order of 0.1–0.2 mm. Northern Rockhopper Penguin eggs harvested in 1999 from Nightingale Island ($n = 113$) were measured similarly by PGR.

Statistical methods

We first examined whether there were differences in egg size between Nightingale and Alex Islands using a multivariate analysis of variance (MANOVA), followed by univariate general linear models for length and breadth and used a Pearson correlation to test for correlations in length and breadth within clutches. We then tested for differences in length and breadth of eggs using a MANOVA. We split the dataset into a training ($n = 189$) and testing ($n = 65$) dataset, and built a linear discriminant function for predicting laying order using the function *lda* in the package MASS in R 3.1.3 (Ripley *et al.* 2012; R Core Team 2015) using backward selection, with egg length and breadth as predictors of laying order. We built the discriminant function using the training dataset and then applied it to the testing dataset (Hastie *et al.* 2009). This discriminant function allowed us to calculate the discriminant score, D, for varying probabilities of assignment to either A- or B-eggs (Fig. 1). We used Cohen's κ (Cohen 1960) to test whether assignment from the discriminant function was better than chance. Results were considered significant when $P < 0.05$

We applied this discriminant function to the separate dataset of egg measurements from 113 eggs harvested on Nightingale Island in 1999 to predict laying order of harvested eggs. We classified eggs with a predicted Pr(A-egg) of >0.67 as A-eggs, those with Pr(A-egg) <0.33 as B-eggs, and the remainder as unknown.

Results

Data had homogenous variances (Levene's test, length: $P = 0.93$, breadth: $P = 0.75$), and though they were not normally distributed

(Shapiro-Wilk's test, length: $W = 0.987$, $P = 0.02$, breadth: $W = 0.973$, $P < 0.001$), log-transforming data did not improve normality (length: $W = 0.988$, $P = 0.03$, breadth: $W = 0.969$, $P < 0.001$). However, for large datasets ($n = 254$), linear models are robust to violations of this assumption (Quinn and Keough 2002).

There was no difference in the size of eggs between the two sites (MANOVA, Wilk's $\lambda = 1.00$, $F_{1,252} = 0.42$, $P = 0.66$). Northern Rockhopper Penguins' A-eggs were significantly smaller than B-eggs (MANOVA, Wilk's $\lambda = 0.38$, $F_{2,251} = 206.9$, $P < 0.001$; Table 1, Fig. 1). Univariate analyses found significant differences in both length ($F_{1,252} = 319.00$, $P < 0.001$) and breadth ($F_{1,252} = 306.50$, $P < 0.001$) between A- and B-eggs. There was inter-individual variation in egg size; females that laid larger B eggs also tended to lay larger A eggs, both in terms of length ($r = 0.49$, $P < 0.001$) and breadth ($r = 0.74$, $P < 0.001$). Our discriminant function using egg length and breadth successfully classified 89% of eggs as A- or B-eggs, which was significantly better than chance (Cohen's $\kappa = 0.82$, $P < 0.001$). The discriminant function was:
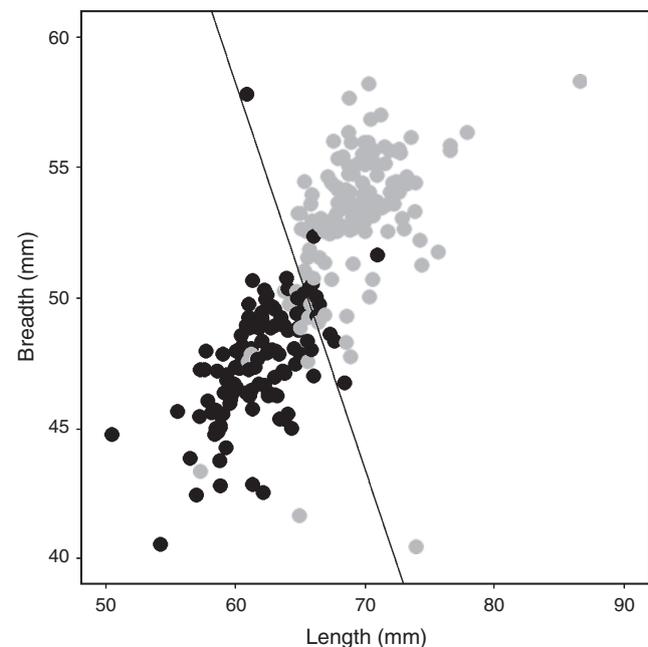

Fig. 1. A- (black) and B- (grey) eggs of Northern Rockhopper Penguins from Nightingale and Alex Islands, Tristan da Cunha. Some data points may overlap. Solid line indicates the 50% cut-off for the discriminant function.

Table 1. Northern Rockhopper Penguins' A-eggs are significantly smaller than B-eggs at Nightingale and Alex Islands, Tristan da Cunha
Wilks' $\lambda = 0.378$, $F_{1252} = 206.93$, $P < 0.001$. Data are mean ± s.d. (range), with subsequent univariate analyses below. $n = 254$ eggs

Egg	Length (mm)	Breadth (mm)
A	61.8 ± 3.8 (50.5–70.9)	47.5 ± 2.3 (40.5–57.8)
B	69.2 ± 3.4 (50.5–86.5)	53.0 ± 2.7 (40.4–58.3)
	$F_{1252} = 319.00$, $P < 0.001$	$F_{1252} = 306.50$, $P < 0.001$

$$D = 0.73 \times Length + 0.50 \times Breadth - 72.39 \quad \text{(Eqn 1)}$$

The probability of being an A-egg can be represented by the logistic equation:

$$Pr(A - egg) = \frac{1}{1 + e^{-D}}. \quad \text{(Eqn 2; Fig. 2)}$$

This resulted in prediction cut-offs of D = 1.099 (Pr(A) = 0.75), 0.708 (Pr(A) = 0.66), 0.00 (Pr(A) = 0.50), –0.708 (Pr(A) = 0.33), and –1.099 (Pr(A) = 0.25). Of the 380 eggs of known laying order, 34 (9%) had a Pr(A-egg) of 33–66% based on the discriminant function, but none were from the same nest.

Using this function, we predicted that of the 113 harvested eggs measured in 1999, 65 (58%) were A-eggs, 41 (36%) were B-eggs and 7 (6%) could not be classified confidently (i.e. the probability of assigning them to A- or B-eggs was <33%; Fig. 3).

Discussion

While it is relatively straightforward to identify A- and B-eggs of Northern Rockhopper Penguins in the nest, there can be some overlap and examining individual eggs may not always result in an accurate assignment. A simple discriminant function based on linear measurements can therefore be used to predict whether single eggs are the first- or second-laid eggs of a clutch. While the linear dimensions of A- and B-eggs overlap, B-eggs are significantly larger and the combination of both measurements can predict most of single eggs.

Discriminant functions have been applied relatively sparingly in wildlife management, in predicting the sex of seabirds caught as bycatch (e.g. Thalmann *et al*. 2007), or harvested legally (Wilhelm *et al*. 2008). In general, they are of the most use when rapid evaluation of individual samples in isolation does not result
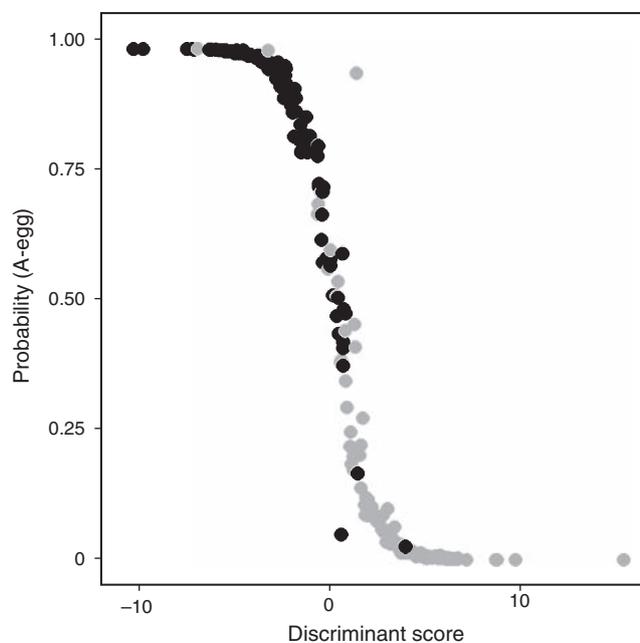
in a consistent or correct assignment to a category, but where measurements of key characters would provide certainty in the classification.

Historically, many penguin species were subject to egg harvesting of varying intensity, although now this is largely a low risk to populations (Trathan *et al*. 2015). Egg harvesting likely contributed to the historical decline in Northern Rockhopper Penguins from hundreds of thousands of pairs in the 19th century to just over 3000 pairs currently on Tristan (Cuthbert *et al*. 2009) and just over 100 000 on Nightingale and Alex Islands (Robson *et al*. 2011). Harvesting causes increased disturbance at breeding sites and removing the larger B-eggs would likely result in poorer breeding success (Williams and Stone 1981; Wilson *et al*. 2010). More than a third of harvested eggs in 1999 were B-eggs, suggesting the practice of harvesting both, or only the larger egg continued through the 20th century.

Managing cultural and subsistence harvests successfully requires adequate tools for monitoring and enforcement, engagement with the local community and the use of both traditional and scientific knowledge. The method we describe here provides a mechanism around which the local community can build part of a sustainable management framework for the harvest of Northern Rockhopper Penguin eggs. As A- and B-eggs can be accurately identified by size, egg harvest can be regulated following defined size classes. In this instance, limiting the harvest to eggs below 65 mm length and 50 mm width would prevent most B-eggs from being collected (Fig. 1) and could be easily enforced using simple tools (e.g. a wooden or metal template with holes 65 mm and 50 mm that allows small A-eggs to pass through). Both local harvesters and enforcement agencies can be trained and educated to discriminate between first- and second-laid eggs, allowing a traditional harvest to continue with sufficient managerial oversight to ensure minimum impacts to the endangered penguin population.

Egg dimorphism is a common feature of *Eudyptes* spp. penguins, with A-eggs being up to 40% smaller than B-eggs in Macaroni Penguins (*E. chrysolophus*) (Williams 1990; Williams 1995). There has been significant egg harvesting in
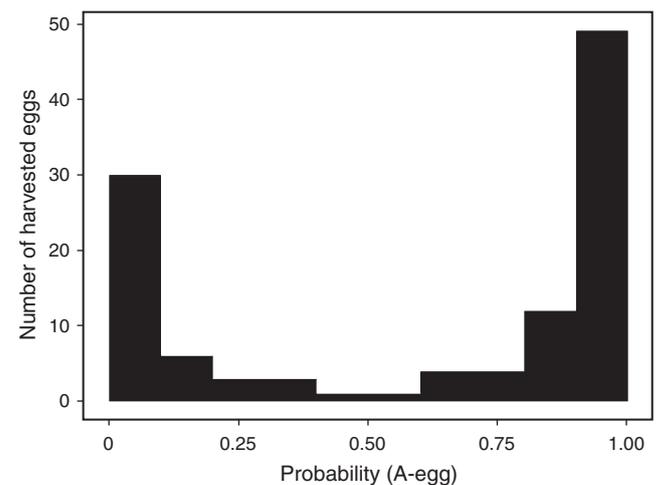

Fig. 2. Discriminant function for the probability that a given Northern Rockhopper Penguin egg was an A-egg. A-eggs are black circles; B-eggs are grey circles. Some data points may overlap.

Fig. 3. Northern Rockhopper Penguin eggs harvested in 1999 were a combination of A- and B-eggs. $n = 113$.

African Penguins (*Spheniscus demersus*) (Frost *et al.* 1976; Siegfried and Crawford 1978; Shannon and Crawford 1999), Adélie Penguins (*Pygoscelis adeliae*) (Bonner 1984), Gentoo Penguins (*P. papua*) (Otley *et al.* 2005; Lynch 2013), and Southern Rockhopper Penguins (*E. chrysocome*) (Pütz *et al.* 2013). It therefore seems probable that this method of determining laying order could be applicable to other crested penguins, particularly where historic or current egg harvesting has the potential to affect populations (Borboroglu and Boersma 2013).

Acknowledgements

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