Factors affecting mortality of shearwaters stranded by light pollution

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Abstract

Every year and across the world, thousands of fledglings of different petrel species crash into human structures because they are disorientated by artificial lights during their first flights. As this phenomenon is rather predictable, rescue campaigns are organized to help birds to reach the ocean, but unfortunately, a low proportion gets hurt or dies. Despite the huge number of affected individuals, and the fact that the problem was detected a long time ago, little is known on this source of mortality. We have studied the factors (i.e. body condition, plumage development, fledging date and sex) influencing the mortality of Cory's Shearwater *Calonectris diomedea* fledglings stranded inland due to light pollution in Tenerife (Canary Islands) during two consecutive breeding seasons (2009 and 2010). Late fledglings showed lower values of a body condition index than early ones. No sex biases were detected, neither considering stranded birds overall, nor for recovery dates or in the body condition of rescued fledglings. Our results indicate that late birds stranded by lights showing abundant down are more susceptible to fatal collisions and that the lights do not selectively kill birds with lower body condition indices. An enhancement of veterinary care should be done during the last part of the fledging period when more fatal collisions occur, especially focused on fledglings with abundant down. More research to determine why some individuals end up disoriented around artificial lights and others do not is urgently needed to minimize or prevent fallouts.

Introduction

Light pollution has been suggested to have an important impact on ecosystems, inducing physiological and behavioural changes in animals, as well as mass mortality episodes for certain species (Longcore & Rich, 2004; Stone, Jones & Harris, 2009; Kempenaers *et al*., 2010). Already identified as an area of interest for biodiversity conservation, the effect of light pollution on organisms is far from being understood (Rich & Longcore, 2006; Hölker *et al*., 2010*a,b*). Disentangling the implications of this source of environmental stress may be necessary to reduce mortality for numerous nocturnal species and threatened populations of different taxa, including birds, sea turtles and numerous insects (Jones & Francis, 2003; Rich & Longcore, 2006; Poot *et al*., 2008; Bourgeois *et al*., 2009).

In the case of petrels (including shearwaters and storm petrels), thousands of fledglings are attracted to lights every year during their first flights from their nests to the open ocean worldwide (Telfer *et al*., 1987; Le Corre *et al*., 2002; Rodríguez & Rodríguez, 2009; Miles *et al*., 2010; Fontaine,

Gimenez & Bried, 2011). This phenomenon, known for a long time (Imber, 1975 and references therein), is termed 'fallout' (Reed, Sincock & Hailman, 1985; Ainley *et al*., 2001). Thanks to rescue campaigns involving the general public, non-government organizations and local authorities, the majority of rescued birds (more than 90%) are released back to the wild, although some casualties occur by starvation, dehydration, predation or road casualties in the short term (Telfer *et al*., 1987; Ainley *et al*., 2001; Le Corre *et al*., 2002; Rodríguez & Rodríguez, 2009; Miles *et al*., 2010; Fontaine *et al*., 2011). In addition, the accumulation of data on rescue campaigns provides basic life-history information useful for the conservation and appropriate management of secretive and rare petrels (e.g. Ainley *et al*., 2001; Le Corre *et al*., 2003; Rodríguez *et al*., 2008; Duffy, 2010; Rodríguez, Rodríguez & Lucas, 2012).

An appropriate knowledge of basic population traits, such as condition and sex ratio, and its relationship with demography, behaviour and population persistence contributes to effective management programs of threatened species (Tella, 2001; Donald, 2007; Ferrer, Newton &

Pandolfi, 2009). For example, the male-biased sex ratio of the critically endangered kakapo *Strigops habroptilus* was a challenge to its recovery. Based on the sex-allocation theory, a decrease of maternal condition has led to an unbiased offspring sex ratio (see Robertson *et al.*, 2006). Despite the fact that rescue campaigns that aim to reduce the artificial light-induced mortality would easily provide data on sex ratio and body condition of rare and threatened petrel populations, no studies have assessed this topic yet.

In this study, we used data from Cory's Shearwater *Calonectris diomedea* rescue campaigns carried out in Tenerife (Canary Islands) during 2 years to assess the general body condition and sex ratio of fallout. Our first specific goal was to assess body condition of fledglings attracted to lights throughout the fledging period, taking into account gender, year, bird status (successfully released/dead) and/or plumage characteristics (abundance of down). Parental food delivery and feeding frequency decrease sharply at the end of chick-rearing period in petrels (Warham, 1990), and on full-moon nights (Klomp & Furness, 1992; Riou & Hamer, 2008; but see also Granadeiro, Burns & Furness, 1998; Granadeiro *et al.*, 2009; Mougin, Jouanin & Roux, 2000*a*). The majority of petrel species are sexually size dimorphic, males being larger and heavier than females and, consequently, more sensitive to adverse conditions (Cockburn, Legge & Double, 2002; Kalmbach & Benito, 2007). Considering the above, we predicted that rescued male fledglings would be in worse body condition than females, especially at later fledging stage and during the years when full moon coincides with the fledging period.

Our second specific goal was to determine whether the number of affected birds and the seasonal pattern of fallouts were sex biased. As a consequence of the predicted worse body condition of fledgling males, we would expect a male-biased sex ratio, especially in fallouts coinciding with full moon. Given the high philopatry exhibited by petrels (Warham, 1990), a sex-biased attraction might impose additional conservation costs of this increasing human-induced source of mortality to the affected populations (particularly if the rescue efforts were less successful than it is estimated).

Our final goal was to determine what factors may explain the fate of rescued birds, that is, comparing individuals released back into the wild versus the ones found dead or too injured to be released. Given the limited funds destined to management and conservation tasks, identifying these factors may be useful to improve rescue campaign designs for Cory's Shearwaters in the Canary Islands and other petrel species elsewhere.

Material and methods

Model species

The Cory's Shearwater *C. diomedea* is a medium-sized seabird (body mass, 600–800 g; wingspan, 112–126 cm). It breeds in Atlantic (Azores, Berlenga, Madeira, Selvagem and Canary Islands; *borealis* subspecies) and Mediterranean islands (*diomedea* subspecies) (Thibault, Bretagnolle &

Rabouam, 1997). Cory's Shearwaters arrive to their breeding grounds in March from their wintering areas located mainly in the South Atlantic Ocean (see González-Solís *et al.*, 2007). Females lay a single egg per clutch in early June and thus only up to one individual may fledge per nest and per year during late October to early November. This species is sexually dimorphic, a fact evident from the early stages of development, with the males being larger and heavier than females (Thibault *et al.*, 1997). However, equal rearing costs have been suggested for both sexes, and an unbiased sex ratio of offspring at nest has been recorded in Mediterranean breeding colonies (Genovart *et al.*, 2005; but see Bretagnolle & Thibault, 1995).

In the Canary Islands (but also in other areas such as Azores, Madeira or Mediterranean archipelagos; Baccetti, Sposimo & Giannini, 2005; Fontaine *et al.*, 2011; Rodrigues *et al.*, 2012), fledglings are strongly attracted to artificial night lights. In Tenerife, the largest of the Canary Islands, between 45 and 61% of fledglings, is estimated to be affected by artificial light attraction (an average of 993 ! 217 fledglings are annually rescued; Rodríguez & Rodríguez, 2009), although a steady increase has been documented since 1990, when rescue campaigns were first organized. This increase runs in parallel to the increase of electricity consumption in the island (Rodríguez *et al.*, 2012).

Study area and rescue campaigns

Tenerife (2034 km^2 and up to 3718 m above sea level) is situated in the central part of the Canary Archipelago (27°37′–29°25′N, 13°20′–18°19′W). Approximately 900 000 people inhabit Tenerife (ISTAC, 2011), and the majority of whom are concentrated along the coast. The main study site is located in the Valle de Güímar, southeast Tenerife (although we also present data from the whole of Tenerife; see below). This area covers 70 km^2, and the landscape is mainly composed of terraced agricultural fields growing different cultivations, loose urban areas as well as small industrial areas. The coastline is dominated by cliffs and rocky boulder shores, where many human settlements are present. Four municipalities (El Rosario, Candelaria, Arafo and Güímar) total approximately 48 000 inhabitants (ISTAC, 2011).

The public was requested to rescue stranded birds through awareness campaigns involving local media, seminars in primary and high schools, and distribution of posters, stickers and T-shirts. Birds were collected by Grupo de Pronto Auxilio de Arafo staff and examined for the subsequent release. Injured birds were handed over to a wildlife rehabilitation centre (WRC) sponsored by the local government (La Tahonilla, Cabildo Insular de Tenerife) and held for rehabilitation or euthanized (see details in Rodríguez & Rodríguez, 2009). During rescue campaigns, fewer than 6% of birds were found dead or euthanized (Rodríguez & Rodríguez, 2009). To obtain an adequate sample size of fledglings fatally stranded, we included all birds collected in the whole of Tenerife Island by La Tahonilla staff. The Güímar birds, dead or alive, plus dead
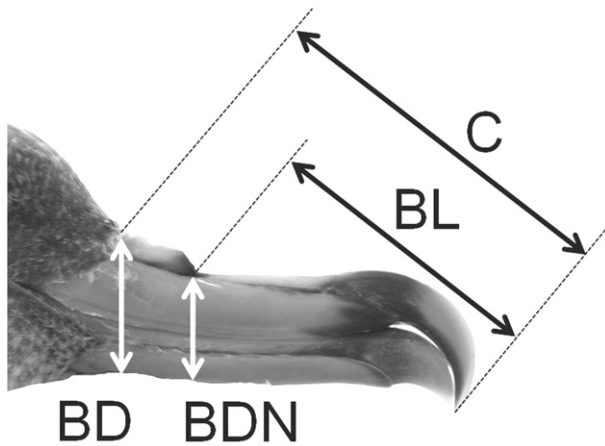
Figure 1 Bill morphometric measurements taken in this study (C, culmen; BL, bill length; BD, bill depth; BDM, bill depth at nostril).

birds from the remaining of Tenerife, were the ones that we measured and sexed in this study.

Moon phase

Our study was conducted during two consecutive years (2009 and 2010) differing in the moon cycle. Thus, during 2009 fallout, full moon coincided with the mean fledging date of Cory's Shearwater (4 November; Rodríguez & Rodríguez, 2009), while in 2010, full moon did not affect the fallout (dates of full moon were 2 November in 2009, and 23 October and 21 November in 2010).

Morphological measurements

For every rescued fledgling, date, recovery location, body mass, wing length (W), tarsus length (T) and four bill morphometric measurements were registered. Bill measurements were culmen (C), from the base of forehead feathers in centre of nasal tube to distant part of the curve of the hooked bill; bill length at nostril (BL), from centre of dorso-medial part of tube to distant part of the curve of the hooked bill; bill depth (BD), from of base of forehead feathers to ventral surface of lower mandible; and bill depth at nostril (BDN), from the base of nasal tube at nostrils to ventral surface of bill (see Fig. 1). The biometrics were taken using a spring balance (nearest 10 g), a rule (nearest 1 mm) and a electronic calliper (nearest 0.01 mm). The presence of down in the head and belly was assessed in an ordinal scale (1 = absence and 3 = wholly covered by down), and the sum of the two values (head and belly) was used as an index of down, ranging from 2 (down absence) to 6 (head and belly wholly covered by down).

A body condition index (BCI) for fledglings was calculated as the standardized residuals of an ordinary least square regression between body mass on body size index (BSI). To avoid spurious relationships of BCI, we checked the key assumptions proposed by Green (2001) and fol-

lowed his recommendations. Thus, we used the first principal component of a principal component analysis (PCA), including six morphometric measurements (W, T, C, BL, BD and BDN; see 'statistical analysis' for details), as a BSI. In addition, we tested the linearity of the functional relationship between body mass and our BSI (Pearson correlation, $r = 0.609$, $P < 0.001$; linear regression, $F_{1,271} = 159.6$, $P < 0.001$), and the standardized residuals showed low correlations with the separate morphometric measurements (all $r < 0.269$). Finally, we used 35 freshly dead Cory's Shearwater fledglings to assess the relationship between fat stores and BCI. Specifically, we weighed fat located around the digestive tube and obtained a significant positive relationship ($r = 0.722$, $P < 0.001$). Recently, the scaled mass index has been proposed as a more reliable BCI (Peig & Green, 2009, 2010); however, this index showed a lower r-value ($r = 0.517$, $P = 0.001$).

Molecular sex determination

Two covert feathers on the belly were collected from each bird as a source of DNA for molecular analysis. The base of the feathers was used to extract the DNA (see Horváth *et al.*, 2005) according to the HotShot protocol (Truett, 2006). We sexed 196 fledglings by polymerase chain reaction (PCR) amplification of CHD genes using primers 2550F and 2718R (Fridolfsson & Ellegren, 1999). PCR was performed in a final volume of 25 mL containing 3.5 mM MgCl$_2$, 1¥ reaction buffer, 0.02% gelatin, 0.2 mM each dNTP, 0.2 mM each primer, and 0.04 U mL^{-1} of Taq DNA polymerase. The PCR profile consisted of 34 cycles of 30 s at 92°C, 30 s at 50°C, 45 s at 72°C and, finally, 5 min at 72°C. PCR products were run out in an agarose gel (2%) by electrophoresis. Gels having a single PCR product (~550 bp) scored as males, while gels having two PCR products of ~550 bp and ~450 bp scored as females.

Statistical analysis

A PCA was used to reduce the number of morphometric measurements from six to one factor (eigenvalues > 1). Bartlett's sphericity test ($c^2 = 970.9$, degrees of freedom = 15, $P < 0.001$) and Kaiser–Meyer–Olkin (KMO) measure (0.72) indicated the adequacy of the correlation matrix. The first factor retained 58.8% of the original variance and reached an eigenvalue of 3.525. Given that all morphometric measurements showed high and positive factor loadings (W = 0.631, T = 0.653, C = 0.847, BL = 0.791, BD = 0.844 and BDN = 0.800) to the first principal component, it was considered as a BSI.

We built a discriminant function analysis to determine the gender of fledglings with no genetic material (for procedures, see Supporting Information Appendix S1). Chi-square and likelihood ratio tests were employed to test differences in the sex ratio of grounded fledglings between fallout seasons (2009 and 2010) and status (released vs. dead), as well as in the down index between sexes and years. To assess the variation of BCI throughout the fallout
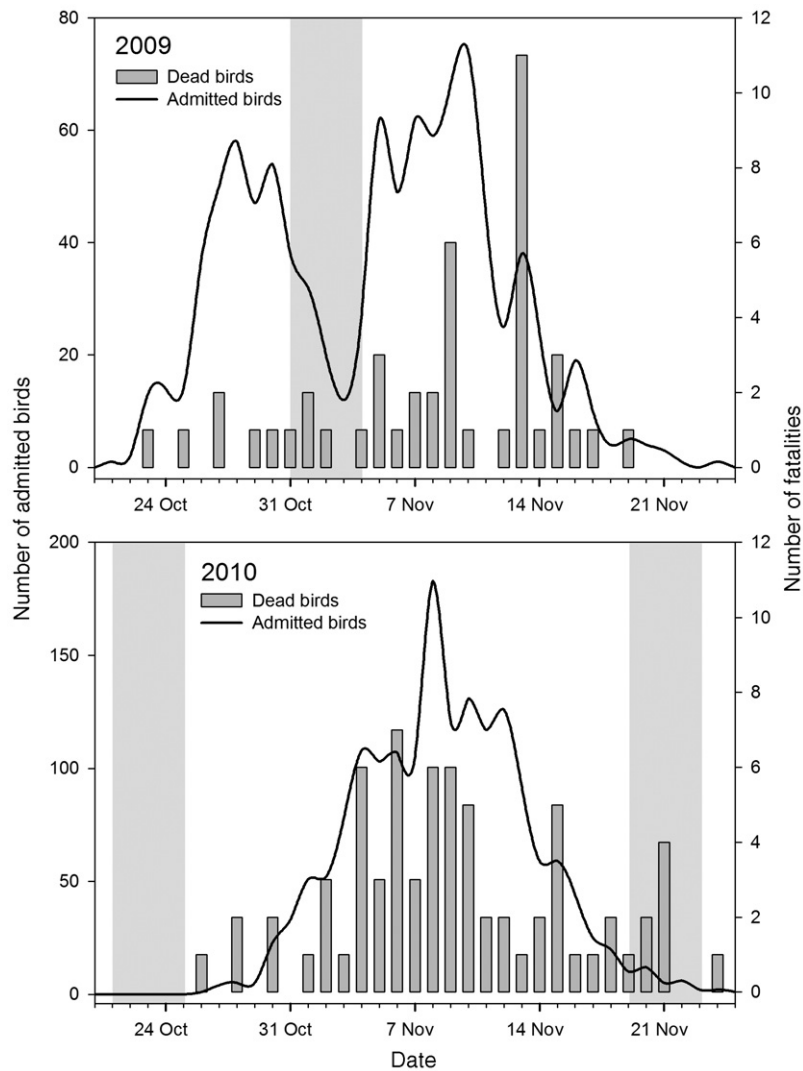
Figure 2 Daily distribution of stranded Cory's Shearwater *Calonectris diomedea* fledglings during the 2009 and 2010 fallouts on Tenerife, Canary Islands. The shaded area indicates a full moon ± 2 days.

period, we constructed a full factorial general linear model with year, status and sex as categorical fixed factors and date (Julian date) as a covariate. Logistic regression models (with binomial errors and a logit link function) were employed to analyze the probability of rescuing a particular sex according to year, status and date, and the probability of rescue of successfully released birds according to year, sex, body condition, date and down index.

Except for the reduced major axis regression necessary to calculate the scaled mass index, which was done using RMA v.1.17 software for Windows (San Diego State University, San Diego, CA, USA) (Bohanak & van der Linde, 2004), statistical analyses were conducted in SPSS Statistics v. 19.0 (IBM Company, Chicago, IL, USA).

Results

In Tenerife, 2749 fledglings were admitted by the La Taho-nilla WRC (984 and 1765 in 2009 and 2010, respectively;

$c^2 = 221.8$, $P < 0.001$; Fig. 2). Ninety-two individuals were found dead or had to be euthanized (22 and 70 in 2009 and 2010, respectively). In Valle de Güímar, 265 fledglings were rescued (97 and 168 birds in 2009 and 2010, respectively; $c^2 = 19.0$, $P < 0.001$).

Body condition

BCI correlated significantly and negatively to date (Fig. 3). The variables 'year', 'status', 'sex' and 'down index' were not significant (Table 1), as well as the 'sex ¥ year' and 'sex ¥ date' interactions (both *P*-values > 0.401). The majority of stranded fledglings (45.1%) had no visible down (Fig. 4). The frequency of down index categories did not vary between successfully released birds and dead ones ($G_4 = 7.407$, $P = 0.116$), but it reached marginal significance between sexes and years ($G_4 = 9.502$, $P = 0.050$ and $G_4 = 9.104$, $P = 0.059$, respectively). The down index did
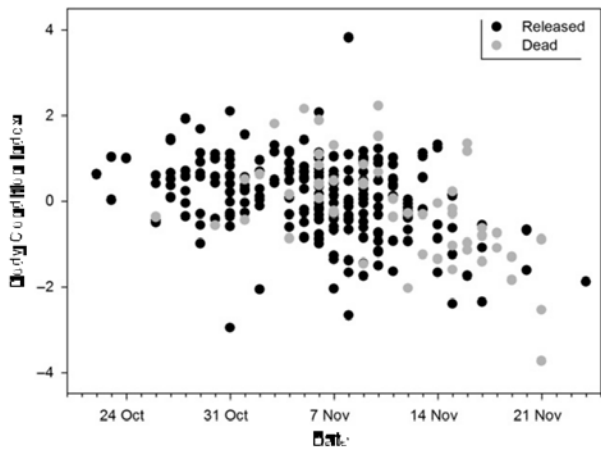
Figure 3 Relationship between date and body condition index (standardized residuals of an ordinary least square regression of body mass on body size index) of both released and dead fledglings.

not correlate with BCI ($r_s = 0.102$, $P = 0.092$) or with date ($r_s = -0.001$, $P = 0.981$).

Sex ratio

Apart from the 196 fledglings that we sexed molecularly, we sexed 77 additional fledglings applying the discriminant function $= 0.782$ (BD) $+ 0.381$ (BL) $+ 0.202$ (T) $- 42.886$, which correctly discriminated 90% of birds (see Supporting Information Appendix S1). Thus, one would expect eight misassignments in the 77 morphometrically sexed birds. For this reason, we conducted separate analyses for the two

datasets: one containing only genetically sexed birds and another one containing genetically and morphometrically sexed birds. Overall, the rescued birds were not sex biased for genetically or morphometrically sexed birds (100 females vs. 96 males; $c^2 = 0.082$, $P = 0.775$; and 36 females vs. 41 males; $c^2 = 0.325$, $P = 0.568$, respectively), and the results did not differ between datasets. In addition, no differences were detected in the sex ratio according to type of sex determination (genetic vs. discriminant function; $G = 0.163$, $P = 0.686$). For all of the above, we only show the results for the larger dataset. Likelihood ratio tests showed no differences in the sex ratio between years (2009 vs. 2010; $G = 0.006$, $P = 0.940$) or status (released vs. dead; $G = 0.001$, $P = 0.974$). The logistic regression model to explore the effect of year, status and date on the probability of rescue of each sex did not include any significant term (Table 1).

Fate of rescued birds

The probability of releasing back to the wild a rescued fledgling decreased with rescue date and abundance of down in head and belly, but it was not explained by body condition (Table 1).

# Discussion

Condition and sex of stranded birds

We have evaluated for the first time the factors affecting both body condition and sex ratio of fledgling shearwaters stranded by light pollution. We found that body condition of Cory's Shearwater fledglings decreased during the fallout

Table 1 Results of a general linear model and binary logistic regressions for body condition index, sex ratio and status variations in relation to year, date, sex and down index

Dependent variable	Model	Estimate ± SE	Statistic (F or Wald)	P
Body condition	General linear model			
	Intercept	2480.275 ± 394.394	39.552	**<0.001**
	Year[a]	0.156 ± 0.120	1.693	0.194
	Status[a]	0.101 ± 0.149	0.459	0.499
	Sex[a]	0.098 ± 0.115	0.732	0.393
	Julian date	−0.061 ± 0.010	39.553	**<0.001**
	Down index	0.011 ± 0.043	0.065	0.799
Sex	Logistic regression			
	Intercept	673.832 ± 863.079	0.610	0.435
	Year[a]	0.013 ± 0.259	0.002	0.960
	Status[a]	0.073 ± 0.322	0.051	0.822
	Julian date	−0.016 ± 0.021	0.610	0.435
Status	Logistic regression			
	Intercept	6493.352 ± 1418.592	20.364	**<0.001**
	Year[a]	0.748 ± 0.381	3.206	0.073
	Sex[a]	0.284 ± 0.343	0.529	0.408
	Body condition	−0.166 ± 0.179	1.020	0.354
	Julian date	−0.159 ± 0.035	20.353	**<0.001**
	Down index	−0.298 ± 0.121	6.016	**0.014**

Significant P-values are in bold.

[a]Parameter estimates were calculated considering a reference value of zero for '2010', 'released' and 'male' levels. SE, standard error.
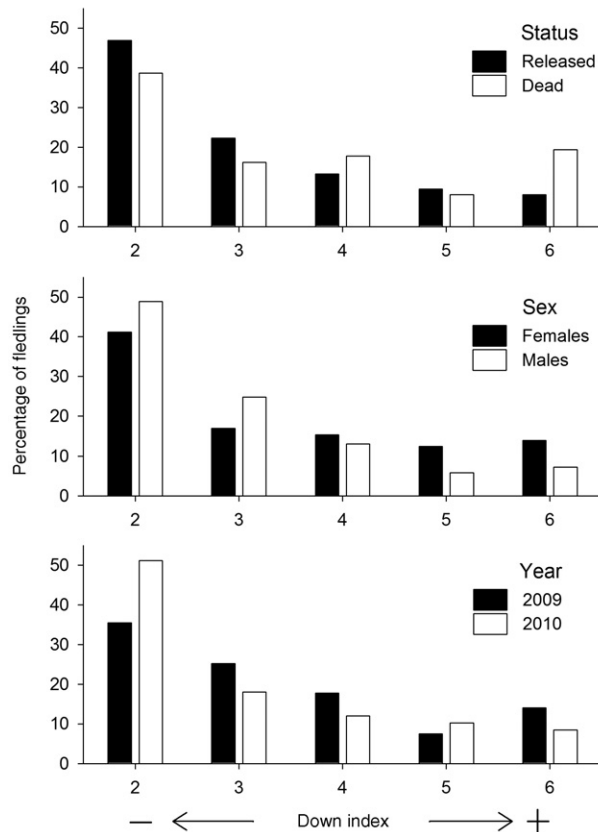
Figure 4 Differences in the down index of Cory's Shearwater *Calonectris diomedea* stranded fledglings among status, sex and year.

period (Fig. 3). The worsening of body condition seems obvious given that parental food delivery and feeding frequency decrease sharply at the end of the chick-rearing period (Ramos *et al*., 2003), and consequently fledglings loose about 28–40 g daily (Zino *et al*., 1987; Mougin *et al*., 2000*b*). Given the remarkable sexual size dimorphism of the species (Thibault *et al*., 1997; see Supporting Information Appendix S1), one would expect a greater sensitivity of male chicks to adverse conditions (Genovart *et al*., 2005). However, and despite parental food delivery being less frequent on full-moon nights (Klomp & Furness, 1992; Riou & Hamer, 2008; but see also Granadeiro *et al*., 1998, 2009; Mougin *et al*., 2000*a*), we did not detect differences in body condition between sexes in two fallouts differing in moon phases (Fig. 2). Interestingly, the body condition indices of successfully released birds was similar to those of fatally attracted birds, and the probability of successfully releasing a bird did not depend on its body condition, suggesting that light-induced mortality do not differentially affect birds in good or bad condition. We have to note that these results are conservative given that the 'fatally attracted birds' category includes birds that could be rescued several days after the birds got stranded, although observing the tail of accumulated birds during the nine fallouts, this does not seem to affect many fledglings (Fig. 3A in Rodríguez & Rodríguez, 2009).

In addition, down index (a surrogate of actual age or development at the time of leaving the nest) did not explain body condition of fledglings, but the probability of successfully releasing a bird decreased with the abundance of down in its head and belly. Thus, if we assumed, as stated above, that down index is a proxy of age, then the younger birds at the end of the fledging period are more susceptible to be fatally affected by light pollution. Additional non-mutually exclusive explanations may be that down negatively affects the aerodynamic, flight capacities of fledglings being diminished, or that down abundance is an indicator of plumage development; thus, fledglings with a high abundance of down have not developed wholly their plumage. On the other hand, the probability of successfully releasing a bird was negatively related with date. This suggests that later birds are somehow forced to fly at the end of fledging period and do it when they are not fully grown.

We failed to detect sex-biased stranding of fledglings in our study. The only previously available information on the sex ratio of petrels stranded by light pollution is based on adult Newell's Shearwaters *Puffinus newelli* on Kauai, Hawaiian archipelago, where an unbiased sex ratio was reported, although it was based on a much smaller sample size (30 birds, males : females ratio = 8 : 9; Ainley *et al*., 2001). For Cory's Shearwater fledglings, sex ratio appears to be equal to parity (Genovart *et al*., 2005), although a male biased sex ratio has been reported in a Mediterranean colony using morphometric discriminant functions and sexual dimorphism in voice, and therefore results should be taken with caution (Bretagnolle & Thibault, 1995). Assuming that offspring sex ratio at fledging does not differ from parity (Genovart *et al*., 2005; but see Bretagnolle & Thibault, 1995), our results indicate that both sexes have the same probability to be attracted to artificial lights as well as to be fatally injured.

Implications for design of rescue campaigns and future research

The life expectancy of rescued birds as well as their recruitment rate into the breeding population is currently unknown. The fledging body mass is likely to play a crucial role in their subsequent survival at sea (Mougin *et al*., 2000*b*). Given the worsening in body condition through the fledging period, an effort should be done to try to rescue birds as soon as they fall and, if veterinary care is not required, to release them immediately. In addition, an enhancement of rescue campaigns during the early stage of fledging is justified (e.g. a more intensive search of grounded fledglings), as fully grown birds with perhaps higher survival prospects in the long-term are involved in the fallout. During the last part of the fledging period when more fatal collisions occur (Fig. 3), a higher effort in the veterinary care should be done (providing food and liquid), especially for fledglings more susceptible to death (i.e. those showing abundant down).

The first weeks following the fledging period are probably difficult for individuals who never before searched for food by themselves. The flapping flights around artificial lights may be too costly for soaring birds like shearwaters. These flights may last for several hours until birds become apparently exhausted and stunned, and crash into human-made structures, such as buildings, wires, electricity pylons or even vehicles. Although it is hard to get a reasonable sample size of control fledglings (i.e. ungrounded fledglings) to assess the effect of these flights on fledgling body condition, it should be a priority to determine the actual effects of light pollution on the critical fledging stage in the life of petrels. Abundance of down is another topic that deserves further study. Specifically, it is necessary to assess its effect on flight performance, waterproofing or insulation of plumage at the sea, and its relation with plumage development.

It is well known that the full moon has an important effect on the number of petrels grounded (Reed *et al*., 1985; Telfer *et al*., 1987; Le Corre *et al*., 2002; Salamolard *et al*., 2007; Rodríguez & Rodríguez, 2009; Miles *et al*., 2010), as fewer fledglings are rescued during years when a full moon overlaps with the fledging peak (Ainley *et al*., 2001; Rodríguez *et al*., 2012; this study). Thus, we can predict how the fallout pattern will be, allowing managers to make optimal decisions on rescue efforts and personnel deployment. Other massive artificial light-induced mortalities of not only passerines but also insects and sea turtles are related to the new moon, suggesting that the same factors may be acting on divergent taxonomical groups (Verheijen, 1981; Salmon & Witherington, 1995; Rich & Longcore, 2006). Therefore, further research into the effect of moon phases could help minimize light-induced mortality of vast numbers of nocturnal animals irrespective of their taxonomical group.

Acknowledgements

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Supporting information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Sexual discriminant function analyses for Cory's Shearwater *Calonectris diomedea borealis* fledglings stranded by light pollution.

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