**Reducing light-induced mortality of seabirds: high pressure sodium lights decrease
the fatal attraction of shearwaters**

Airam Rodríguez^{a,b,*}, Peter Dann^a, and André Chiaradia^a

^a *Research Department, Phillip Island Nature Parks, Victoria, Australia*

^b *Department of Evolutionary Ecology, Estación Biológica de Doñana (CSIC), Seville,
Spain*

*** Corresponding author:** Airam Rodríguez, Department of Evolutionary Ecology,
Estación Biológica de Doñana (CSIC), Avda. Américo Vespucio, S/N, 41092, Seville,
Spain; E-mail: airamrguez@ebd.csic.es; Phone: +34 954 23 23 40

Abstract

The use of artificial light at night and its ecological consequences are increasing around the world. Light pollution can lead to massive mortality episodes for nocturnally active petrels, one of the most threatened avian groups. Some fledglings can be attracted or disoriented by artificial light on their first flights. Studies testing the effect of artificial light characteristics on attractiveness to seabirds have not provided conclusive results and there is some urgency as some endangered petrel species experience high light-induced mortality. We designed a field experiment to test the effect of three common outdoor lighting systems with different light spectra (high pressure sodium, metal halide and light emitting diode) on the number and the body condition of grounded fledglings of the short-tailed shearwater *Ardenna tenuirostris*. A total of 235 birds were grounded during 99 experimental hours (33 hours for each treatment). 47% of birds were grounded when metal halide lights were on, while light emitting diode and high pressure sodium lights showed lower percentages of attraction (29% and 24%). Metal halide multiplied the mortality risk by a factor of 1.6 and 1.9 respectively in comparison with light emitting diode and high pressure sodium lights. No differences in body condition were detected among the birds grounded by the different lighting systems. We recommend the adoption of high pressure sodium lights into petrel-friendly lighting designs together with other light mitigation measures such as light attenuation, lateral shielding to reduce spill and appropriate orientation.

Keywords: artificial light, fledging, illumination, light pollution, mortality, seabird

1. Introduction

The increasing use of artificial light at night is causing a loss of the natural nightscapes worldwide (Falchi et al., 2016). Light pollution is an emerging threat to biodiversity conservation by disrupting circadian rhythms, affecting natural behaviours, reproduction, animal movement or endocrine systems, and finally, influencing the ecosystem functioning by cascading effects (Gaston et al., 2014; Hölker et al., 2010; Longcore and Rich, 2004). Although marine environments are mostly free of artificial light, most coastal areas are affected by light pollution at night (Davies et al., 2014). Artificial lights along the coast can cause direct and incidental mass mortality events in endangered marine taxa, e.g. turtles or seabirds (Rich and Longcore, 2006; Rodríguez et al., 2017a). Despite the multiple effects on human health and biodiversity, artificial light is steadily proliferating in the night environment led by improvements in luminous efficiency (Kyba et al., 2014). Thus, the determination of the impact of the different artificial lighting systems on biodiversity should be a priority for developing appropriate lighting policies to enable better coastal planning and conservation practices.

Fledglings of nocturnal petrel species (including shearwaters and storm-petrels) are attracted to artificial lights during their first flights from nest-burrows to the ocean, often colliding with human structures or the ground. If they survive the collision, they are grounded in artificially lit areas and susceptible to being killed by incidental threats (vehicle collision, predation, starvation or dehydration) (Ainley et al., 2001; Le Corre et al., 2002; Rodríguez et al., 2012a; 2014). To mitigate light-induced mortality of petrels, rescue programs have been implemented in several locations around the world (Rodríguez et al., 2017a). However, pre-emptive measures, that reduce the attractiveness of artificial lighting to seabirds, would be much more effective at the population level. To our knowledge, there is no published information on whether

seabird attraction to artificial lights is related to the type of lights or individual traits of the seabirds. Here, we test the effect of three commonly used lighting systems with different light spectra (metal halide –MH, high pressure sodium –HPS– and light emitting diode –LED) on the attraction of short-tailed shearwater (*Ardenna tenuirostris*) fledglings, a species severely affected by light pollution (Rodríguez et al., 2014). We also test if body condition of grounded fledglings differs among lighting systems. Why petrels are attracted to lights is not entirely understood, but it may be related to food as petrels could confuse lights with natural bioluminescent prey or associate light with food during the nestling period at their nest-burrows (see Rodríguez et al., 2017a). Although short-tailed shearwater fledglings attracted by artificial lights do not seem handicapped, as their body condition is similar to those of adults (Rodríguez et al., 2017b), degree of attraction to lighting systems could be mediated by body condition. Body condition at fledging is a proxy to greater likelihood of survival and recruitment in long-lived seabirds (Becker and Bradley, 2007; Maness and Anderson, 2013). Thus, attraction of birds in good condition, i.e. those with higher survival and recruitment probabilities, to a particular lighting system would worsen the impact of such light for petrel populations. Apart from lighting systems, other factors appear to play a role in the number of seabirds attracted to lights. First, birds tend to fledge early in the night (Reed et al., 1985; Rodríguez et al., 2015), and therefore, it was expected that the number of grounded birds would increase during the first nocturnal hours. Second, fledging is a synchronous process leading to high number of birds fledging around a peak date (27-28 April for the short-tailed shearwater; Rodríguez et al., 2014). Third, fledging date is favoured by strong winds which give a lift to flight-inexperienced fledglings (Rodríguez et al., 2014; Skira, 1991). Fourth, the number of grounded birds is reduced during full moon nights (Le Corre et al., 2002; Rodríguez and Rodríguez, 2009; Telfer et al., 1987).

Fifth, the number of attracted birds in a year is related to the number of fledglings produced by the population in that particular year, i.e. the higher breeding success the higher the numbers of grounded birds (Day et al., 2003; Rodríguez et al., 2012b).

2. Material and methods

Our study was conducted on Phillip Island, south-eastern Australia, where natural night skylines unpolluted by artificial lights are available adjacent to short-tailed shearwater breeding colonies (Figure 1a). Phillip Island is relatively low with a maximum altitude about 112 m above sea level. It holds around 543,000 breeding pairs of short-tailed shearwaters (Harris et al., 1980), which is more than 1% of its global breeding population (BirdLife International, 2017), mainly distributed along the south coast (Figure 1a). The short-tailed shearwater nests in dense colonies generally in sandy soils. Adults start migration before their chicks fledge and consequently fledglings depart the colony in the absence of their parents. Fledglings try to reach the ocean on their first flights.

Our experiment was conducted in the overflow car park at Phillip Island Nature Parks on the Summerland Peninsula (-38.505942°S, 145.149486°E), which is a 13,000 m² grassed area surrounded by some unlit buildings and short-tailed shearwater colonies (Fig 1b). At the experiment site, masts held the three types of lamps (MH, HPS and LED) at the same height and orientation at each mast. Five masts of 3-5 m high supported the lamps used during the experiment (Figure 1b,c). The three light types employed in our study are commonly used in outdoor facilities (e.g. car parks, sport stadiums and industrial areas) and they emit different spectra (Figure 2a; Table 1). MH

and HPS bulbs emit light in 360 degrees in every direction, and for this reason they were housed in similar luminaries. In contrast, LED emits light in one direction.

To assess the potential attraction of shearwater fledglings to the three lighting types, we designed an experiment in which every treatment (light type) was replicated every night. We lit the area at night during the fledging period and counted the number of grounded birds on the lit field. The experiment was repeated over three fledging seasons (2014: 22 April-4 May; 2015: 19 April-5 May; 2016: 26-29 April). To account for the high variability in number of groundings from night to night, we turned on each lighting type for one hour in a random order each night. The same type of light (MH, HPS and LED) was on in the five masts during each experimental hour. We also had a period of 15-minutes in darkness between treatments to avoid potential attractive effects of the previous treatment on the birds. First light-treatment was turned on 45-60 minutes after sunset. We ran the experiments in the first hours of darkness (three experimental hours in total plus two 15-minutes gaps) as they coincide with the peak of fledging time (Reed et al., 1985; Rodríguez et al., 2015). By randomly sequencing the three treatments, we controlled for any changes in hourly fledgling rate through the night.

Grounded birds were collected and kept in boxes. Each individual was marked with a permanent marker pen on the toe webbing for identification and released in the closest colony at the end of each experimental night. Recaptured birds (five birds) were not included in the analyses. In 2015, body mass (g) and four biometric variables (wing, tarsus, bill length and bill length) were measured from grounded birds in the treatments of the experiment. The biometric variables were taken using an electronic balance (nearest 5 g), a ruler (nearest 1 mm) and an electronic calliper (nearest 0.01 mm). To obtain a size indicator of the grounded birds, we ran a principal component analysis (PCA) on centered and scaled morphometric variables (wing, tarsus and bill length, and

bill depth) and the first principal component was used as a body size index (BSI). The first principal component retained 54% of variation. The four morphometric variables showed positive factor loadings (factor loadings: 0.47, 0.51, 0.49 and 0.52 for wing, tarsus, and bill length, and bill depth) and highly significant correlations to the first principal component (Figure S1). Then, we run a linear model of body mass on BSI (the first principal component). This regression showed a $R^2 = 0.33$ and it was statistically significant ($F_{1, 133} = 65.2$, $P < 0.001$). Diagnostic plots indicated that model assumptions were not violated (see Figure S2). Finally, we extracted the standardized residuals of this model and used them as a body condition index (BCI), where positive and negative values indicate that birds are heavier and lighter than the average in the population, respectively (Green, 2001; Rodríguez et al., 2012a, 2017b).

To control for the confounding variables noted in the introduction, i.e. fledging time/order and wind strength, moon light and inter-annual breeding success, we added five predictors: 1) Order of light treatment (three-level factor: first, second and third). 2) Quadratic term of fledging date (continuous variable ranging from 19 April to 5 May). 3) Wind speed (km/h) taken from an automated meteorological station located at Rhyll, Phillip Island, and distant 15 km from the study area (Bureau of Meteorology reference: 086373). The station provides wind data every 30 minutes and we calculated the average for the two readings of each experimental hour (treatment). 4) Moon light or luminance (continuous variable) measured as the percentage of luminance at full moon at zenith at distance equal mean equatorial parallax (Austin et al., 1976). We calculated moon luminance for each 10-minute periods by using the moonlight Fortran software (Austin et al., 1976) and we assigned the maximum moon luminance to each experimental hour. 5) Year as a three-level factor to account for annual variation in breeding success.

We used generalised linear mixed models (GLMMs) with log link and Poisson error distributions to assess whether the number of grounded birds differs between light treatments (three-level factor). To control for the dependence in the number of grounded birds per light treatment in a single night, night was included as a random factor. To control for confounding variables, i.e. variables affecting the number of attracted birds (see above), we conducted GLMMs adding these predictors plus light treatment factor. To avoid over parameterization, only two predictors were included in each model (light treatment plus predictor). To assess whether body condition of grounded birds differs between lighting types, a linear model was conducted including body condition index as response variable and light treatment as a factor. Models were compared to null models, i.e. including only the intercept, using the ‘anova’ function (stats package) and assumptions were checked using diagnostic plots (Supplementary material). Statistical analyses were conducted in R version 3.3.2 (R Core Team, 2016). The function ‘prcomp’ (stats package) was employed to conduct the principal component analysis (PCA). Linear models and generalised linear mixed models were conducted using the functions ‘lm’ (stats package) and ‘glmer’ (lme4 package) (Bates et al., 2015). Model assumptions of generalised linear mixed models were checked through a simulation-based approach using the ‘DHARMA’ package (Hartig, 2016).

3. Results

A total of 235 short-tailed shearwater fledglings were grounded during the 33 experimental nights (99 hours; 33 hours for each treatment) in the three annual fledging periods. Pooling all nights, the highest number of grounded fledglings was reached when MH lights were on ($\chi^2_2 = 19.974$; $P < 0.001$; 110, 68 and 57 birds for MH, LED

and HPS lights, respectively). Eight out of the 235 birds were killed or subsequently euthanized after fatal collision with the ground or light-posts (4, 3 and 1 birds for MH, LED and HPS lights). The GLMM including just the light treatment was significant with regard to the null model, i.e. including only the intercept term ($\chi^2_2 = 19.209$; $P < 0.001$; Figure 2b). Light treatment was also significant in all the GLMMs including additional variables (all P-values < 0.003 ; Supplementary material). In 2015, 135 grounded shearwaters were captured and measured. Body condition was similar between the shearwaters grounded by the different lighting types (Figure 2c), as the model was not better than the null model ($F_{2,132} = 1.908$; $P = 0.153$).

4. Discussion

The number of grounded birds differed among light types, with MH being the light type attracting the highest number of the short-tailed shearwater fledglings. LEDs were second highest light type in causing grounded birds, although no statistical differences were apparent in comparison with HPS. Body condition of birds grounded by each lighting type was similar, indicating that attraction power of each lighting type did not depend on body condition, and more interestingly that no lighting system selectively attracted birds with higher survival and recruitment probabilities, i.e. birds in good body condition.

Differences in the number of grounded birds per light type may be explained by the visual systems of shearwaters. The retina of the congeneric wedge-tailed shearwater (*Ardenna pacifica*) have five visual pigments with maximum absorbance at 406-566 nm (Hart, 2004). Assuming a similar visual system, short-tailed shearwater fledglings could be more sensitive to MH and LED lighting, which produce a very cool light (blue) and a

wider emission spectrum, than HPS which produces warmer light (red/orange) and low emissions under 550 nm (Table 1; Figure 2a). Thus, shearwaters are likely to perceive lights differently. Given they display an attraction response, heightened perception may lead to heightened attraction. Our results on the higher number of grounded birds by MH and LED than HPS lights, agree with the possibility that MH and LED lights are appreciably brighter for shearwaters than HPS lights, thus increasing the attraction response.

Our results agree with other studies on other taxa in which HPS lights affect behaviour less than MH or LED lights, e.g. bats (Stone et al., 2015) or invertebrates (Pawson and Bader, 2014), but contrast with those found for songbirds at off-shore platforms. Nocturnal migrating songbirds are more attracted by light with visible long-wavelength radiation (red and white) than by light with less or no visible long-wavelength radiation (blue and green) (Poot et al., 2008). Thus, adopting taxa-specific recommendations for the effect of artificial lights is crucial.

Designing experiments to study the potential attraction of different light types to seabirds is a challenging task, due to the intrinsic seabird natural traits, the low number of colonies and the vast extensions of cities and their associated light pollution (Reed, 1987, 1986; Reed et al., 1985). Reed and collaborators conducted two field experiments changing light characteristics (polarization and spectra), but failed to reduce light attraction in Newell's shearwaters *Puffinus newellii* (Reed, 1987, 1986). Despite these inconclusive results, light signatures (wavelength and intensity) have been changed around nesting colonies around the world to mitigate light-induced mortality. However, these actions have been conducted without any scientific evidence and their effectiveness has not been appropriately assessed (Rodríguez et al., 2017a). Our experimental study sheds some light on the potential effect of commercially available

lighting systems, providing first-hand information for the lighting management around seabird breeding grounds. If artificial lights cannot be completely avoided, we strongly recommend that HPS lights, or filtered LED and MH lights with purpose-designed filters for lower emission spectra, should be the only external lights used in proximity to shearwater colonies. The type of light must be adopted together with other light reduction actions (KSHCP, 2017). Light should be as dim as possible to be fit the purpose, and should be correctly oriented towards the target area or object to avoid skyward light spill. Shielding and cut-off designs for luminaries can also help to avoid unnecessary light spread. Finally, turning off the lights when not required or using motion sensors to turn on/off the lights would contribute to reducing light pollution (for a complete list of light mitigation actions see KSHCP, 2017). More research is needed to further understand the role of emission spectra on the potential attraction of seabirds and the impact of seabird-friendly lighting on sympatric organisms.

Acknowledgments. We are grateful to the volunteers during fieldwork, especially to Rut Martínez and Manuel Cáceres, and the Phillip Island Nature Parks personnel. Comments of Mike Weston and an anonymous reviewer improved the manuscript.

Funding. This study was supported by a Marie Curie International Outgoing Fellowship within the 7th European Community Framework Programme (330655 FP7-PEOPLE-2012-IOF). A.R. benefited from a Juan de la Cierva contract from the Spanish Ministry of Economy and Competitiveness (IJC-2015-23913).

Ethics. Procedures were approved by the Animal Ethics Committee, Phillip Island Nature Parks (Project 1.2014), and the Department of Environment and Primary Industries, Victorian State Government (Permit 10007170).

Data accessibility. Data will be available in Digital.CSIC, the institutional repository of the Spanish National Research Council.

Competing interests. The authors declare no competing interests.

References

- Ainley, D.G., Podolsky, R., Deforest, L., Spencer, G., 2001. The Status and Population Trends of the Newell's Shearwater on Kaua'i: Insights from Modeling. *Stud. Avian Biol.* 22, 108–123.
- Austin, R.H., Phillips, B.F., Webb, D.J., 1976. A Method for Calculating Moonlight Illuminance at the Earth's Surface. *J. Appl. Ecol.* 13, 741–748.
- Bates, D., Mächler, M., Bolker, B.M., Walker, S.C., 2015. Fitting Linear Mixed-Effects Models using “lme4.” *J. Stat. Softw.* 67, 1–48. doi:10.18637/jss.v067.i01
- Becker, P.H., Bradley, S.J., 2007. The role of intrinsic factors for the recruitment process in long-lived birds. *J. Ornithol.* 148, 377–384. doi:10.1007/s10336-007-0157-x
- BirdLife International, 2017. Important Bird and Biodiversity Area factsheet: Phillip Island. [WWW Document]. URL <http://datazone.birdlife.org/site/factsheet/phillip-island-iba-australia> (accessed 6.12.17).
- Davies, T.W., Duffy, J.P., Bennie, J., Gaston, K.J., 2014. The nature, extent, and ecological implications of marine light pollution. *Front. Ecol. Environ.* 12, 347–355. doi:10.1890/130281
- Day, R.H., Cooper, B.A., Telfer, T., 2003. Decline of Townsend's (Newell's) Shearwaters (*Puffinus auricularis newelli*) on Kauai, Hawaii. *Auk* 120, 669–679. doi:10.2307/4090098
- Falchi, F., Cinzano, P., Duriscoe, D., Kyba, C.C.M., Elvidge, C.D., Baugh, K., Portnov, B.A., Rybnikova, N.A., Furgoni, R., 2016. The new world atlas of artificial night sky brightness. *Sci. Adv.* 2, e1600377. doi:10.1126/sciadv.1600377
- Gaston, K.J., Duffy, J.P., Gaston, S., Bennie, J., Davies, T.W., 2014. Human alteration of natural light cycles: causes and ecological consequences. *Oecologia* 176, 917–931. doi:10.1007/s00442-014-3088-2
- Green, A.J., 2001. Mass/length residuals: measures of body condition or generators of spurious results? *Ecology* 82, 1473–1483. doi:10.1890/0012-9658(2001)082[1473:MLRMOB]2.0.CO;2
- Harris, M.P., Brown, R.S., Deerson, D.M., 1980. Populations of Little Penguins, Short-Tailed Shearwaters and Other Seabirds on Phillip Island, Victoria, 1978. *Emu* 81, 20–28.
- Hart, N.S., 2004. Microspectrophotometry of visual pigments and oil droplets in a marine bird, the wedge-tailed shearwater *Puffinus pacificus*: topographic variations in photoreceptor spectral characteristics. *J. Exp. Biol.* 207, 1229–1240. doi:10.1242/jeb.00857

297 Hartig, F., 2016. DHARMA: Residual Diagnostics for Hierarchical (Multi-Level/Mixed)
 298 Regression Models [WWW Document]. Packag. “DHARMA” version 0.1.2. URL
 299 <https://cran.r-project.org/web/packages/DHARMA/index.html> (accessed 11.19.16).

300 Hölker, F., Wolter, C., Perkin, E.K., Tockner, K., 2010. Light pollution as a biodiversity
 301 threat. *Trends Ecol. Evol.* 25, 681–682. doi:10.1016/j.tree.2010.09.007

302 KSHCP, (Kaua‘i Seabird Habitat Conservation Program), 2017. Lighting for homes and
 303 businesses [WWW Document]. Kaua‘i Seab. Habitat Conserv. Progr. URL
 304 <http://kauaiseabirdhcp.com/lighting-homes-businesses/> (accessed 6.25.17).

305 Kyba, C.C.M., Hänel, A., Hölker, F., 2014. Redefining efficiency for outdoor lighting.
 306 *Energy Environ. Sci.* 7, 1806. doi:10.1039/c4ee00566j

307 Le Corre, M., Ollivier, A., Ribes, S., Jouventin, P., 2002. Light-induced mortality of
 308 petrels: a 4-year study from Réunion Island (Indian Ocean). *Biol. Conserv.* 105,
 309 93–102. doi:10.1016/S0006-3207(01)00207-5

310 Longcore, T., Rich, C., 2004. Ecological light pollution. *Front. Ecol. Environ.* 2, 191–
 311 198. doi:10.1890/1540-9295(2004)002[0191:ELP]2.0.CO;2

312 Maness, T.J., Anderson, D.J., 2013. Predictors of Juvenile Survival in Birds. *Ornithol.*
 313 *Monogr.* 78, 1–55. doi:10.1525/om.2013.78.1.1.1

314 Pawson, S.M., Bader, M.K.F., 2014. LED lighting increases the ecological impact of
 315 light pollution irrespective of color temperature. *Ecol. Appl.* 24, 1561–1568.
 316 doi:10.1890/07-1650.1

317 Poot, H., Ens, B.J., Vries, H., Donners, M.A.H., Wernand, M.R., Joop, M.M., 2008.
 318 *Green Light for Nocturnally Migrating Birds.* *Ecol. Soc.* 13, 47.

319 R Core Team, 2016. R: A Language and Environment for Statistical Computing.

320 Reed, J.R., 1987. Polarizing Filters Fail to Reduce Light Attraction in Newell’s
 321 Shearwaters. *Wildl. Soc. Bull.* 15, 596–598.

322 Reed, J.R., 1986. Seabird Vision: Spectral Sensitivity and Light-Attraction Behavior.
 323 The University of Wisconsin-Madison.

324 Reed, J.R., Sincock, J.L., Hailman, J.P., 1985. Light Attraction in Endangered
 325 Procellariiform Birds: Reduction by Shielding Upward Radiation. *Auk* 102, 377–
 326 383. doi:10.2307/4086782

327 Rich, C., Longcore, T., 2006. Ecological Consequences of Artificial Night Lighting.
 328 Island Press, Washington, USA.

329 Rodríguez, A., Burgan, G., Dann, P., Jessop, R., Negro, J.J., Chiaradia, A., 2014. Fatal
 330 Attraction of Short-Tailed Shearwaters to Artificial Lights. *PLoS One* 9, e110114.
 331 doi:10.1371/journal.pone.0110114

332 Rodríguez, A., Holmes, N.D., Ryan, P.G., Wilson, K.-J., Faulquier, L., Murillo, Y.,
 333 Raine, A.F., Penniman, J.F., Neves, V., Rodríguez, B., Negro, J.J., Chiaradia, A.,
 334 Dann, P., Anderson, T., Metzger, B., Shirai, M., Deppe, L., Wheeler, J., Hodum,
 335 P., Gouveia, C., Carmo, V., Carreira, G.P., Delgado-Alburquerque, L., Guerra-
 336 Correa, C., Couzi, F.-X., Travers, M., Corre, M. Le, 2017a. Seabird mortality
 337 induced by land-based artificial lights. *Conserv. Biol.* doi:10.1111/cobi.12900

338 Rodríguez, A., Moffett, J., Revoltós, A., Wasiak, P., McIntosh, R.R., Sutherland, D.R.,
 339 Renwick, L., Dann, P., Chiaradia, A., 2017b. Light pollution and seabird

340 fledglings: Targeting efforts in rescue programs. *J. Wildl. Manage.* 81, 734–741.
341 doi:10.1002/jwmg.21237

342 Rodríguez, A., Rodríguez, B., 2009. Attraction of petrels to artificial lights in the
343 Canary Islands: effects of the moon phase and age class. *Ibis* 151, 299–310.
344 doi:10.1111/j.1474-919X.2009.00925.x

345 Rodríguez, A., Rodríguez, B., Curbelo, Á.J., Pérez, A., Marrero, S., Negro, J.J., 2012.
346 Factors affecting mortality of shearwaters stranded by light pollution. *Anim.*
347 *Conserv.* 15, 519–526. doi:10.1111/j.1469-1795.2012.00544.x

348 Rodríguez, A., Rodríguez, B., Lucas, M.P., 2012. Trends in numbers of petrels attracted
349 to artificial lights suggest population declines in Tenerife, Canary Islands. *Ibis* 154,
350 167–172. doi:10.1111/j.1474-919X.2011.01175.x

351 Rodríguez, A., Rodríguez, B., Negro, J.J., 2015. GPS tracking for mapping seabird
352 mortality induced by light pollution. *Sci. Rep.* 5, 10670. doi:10.1038/srep10670

353 Skira, I., 1991. The short-tailed shearwater: a review of its biology. *Corella* 15, 45–52.

354 Stone, E.L., Wakefield, A., Harris, S., Jones, G., 2015. The impacts of new street light
355 technologies: experimentally testing the effects on bats of changing from low-
356 pressure sodium to white metal halide. *Philos. Trans. R. Soc. B Biol. Sci.* 370,
357 20140127–20140127. doi:10.1098/rstb.2014.0127

358 Telfer, T.C., Sincock, J.L., Byrd, G.V., Reed, J.R., 1987. Attraction of hawaiian
359 seabirds to lights: conservation efforts and effects of moon phase. *Wildl. Soc. Bull.*
360 15, 406–413.

361

362 **Table 1.** Characteristics of light systems used in the experiment.

Light	Comercial reference	Lamp Wattage (W)	Color Temperature (K)	Luminous Flux (Lm)
High pressure sodium (HPS)	SON-T 400W/220 E40 1SL	400	2000 (warm)	48000
Metal halide (MH)	MASTER HPI-T Plus 400W/645 E40 1SL	400	4500 (cool)	32000
Light emitting diode (LED)	VBLFL-855-4-40	200	4536 (cool)	18111

363

364

Figure 1. (a) Phillip Island map showing distribution of breeding colonies, study site (grey circle) and light pollution levels taken from a nocturnal satellite imagery; NOAA National Geophysical Data Center; available at http://ngdc.noaa.gov/eog/viirs/download_monthly.html. (b) Map of the study area showing the light posts and the lit area. (c) Nocturnal picture showing two light-posts and the moon.

Figure 2. Spectral composition (a) of the lighting types used (data provided by manufacturer). Vertical dashed and solid lines indicate the wavelength of maximum absorbance of visual pigment of cones and rods for *Ardena pacifica* (Hart, 2004). Mean number per hour (b) and body condition (c) of short-tailed shearwater fledglings grounded by lighting types. In (b) bars show mean $\pm$ s.e. Different capital letters indicate significant differences between levels.