Artificial lights and seabirds: is light pollution a threat for the threatened Balearic petrels?

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Abstract

Petrels are among the most threatened group of birds. On top of facing predation by introduced mammals and incidental bycatch, these seabirds have to deal with an emerging threat, light pollution, which is increasing globally. Fledglings are disorientated and attracted to artificial lights in their maiden night flights from their nests to the sea. Once grounded, they are exposed to multiple threats leading to high mortality. We report on numbers of three petrel species (Balearic shearwater *Puffinus mauretanicus*, Scopoli's shearwater *Calonectris diomedea*, and European storm-petrel *Hydrobates pelagicus*) rescued on the Balearic Islands, Mediterranean Sea, in the period 1999-2013. We assessed the proportion of grounded fledglings in the population and colonies impact based on radiance levels measured from a nocturnal satellite image. We also calculated the radius of light pollution impact. At least 304 fledgling birds were found stranded due to attraction to artificial lights, 8.5% of them being fatally affected. Proportion of grounded fledglings ranged between 0.13-0.56% of the fledglings produced annually. The body mass of Balearic and Scopoli's shearwater fledglings decreased with rescue date. Light-induced mortality increased during fledging period for Scopoli's shearwaters. Birds were rescued at a mean distance of 4,833 m from the nearest colony and between 30-47% of colonies were exposed to light-polluted areas. Although impact seems to be low for all species, urban development and, consequently, the increase in light pollution in the proximities of the colonies should be taken into account to reduce as much as possible this emerging source of mortality.

Keywords artificial lights, attraction, Balearic Islands, disorientation, illumination, light pollution, mortality, seabird

Running Head

Balearic seabirds attracted to lights

Introduction

Light pollution, i.e. the alteration of natural light levels at night as consequence of human structures, is increasing worldwide and it has been recently recognized as a threat for biodiversity (Hölker et al. 2010a,b). One of the negative effects of light pollution on animals is disorientation in their movements, with consequences for their fitness and survival (Longcore and Rich 2004; Gaston et al. 2014). Land-breeding marine animals, such as sea turtles and seabirds, are strongly affected by lights when hatchlings or fledglings direct toward the sea for the first time in their lives (Rich and Longcore 2006). These events can cause high mortality in one of the most endangered groups of birds, the petrels (Order Procellariiformes; Croxall et al. 2012), as fledglings are grounded in lit areas and susceptible to collisions with human infrastructures or vehicles, predation by introduced predators, starvation or dehydration (a phenomenon called fallout; Reed et al. 1985; Telfer et al. 1987; Ainley et al. 2001; Le Corre et al. 2002; Rodríguez and Rodríguez 2009; Miles et al. 2010; Fontaine et al. 2011; Rodríguez et al. 2014a). Because petrels are long-lived birds, population dynamics are especially sensitive to adult survival. However, light pollution affecting mainly fledglings has been recognized as an important mortality source, which, in addition to other threats, could endanger the survival of petrel populations (Ainley et al. 2001; Fontaine et al. 2011; Griesemer and Holmes 2011). Apart from attracting fledglings to lit areas, light pollution could also modify the behaviour of predators of nocturnal colony-visiting petrels. Burrow-nesting petrels visit colonies at night apparently to avoid predators (Miles et al. 2013), and thus an increase in light levels at colonies as a consequence of light pollution can increase the predation by diurnal predators (Oro et al. 2005).

Balearic Islands are among the most popular touristic destinations in the Mediterranean Sea, highly populated and with increasing light pollution levels (IBESTAT 2014; de Miguel et al. 2014). Despite high anthropogenic transformation of the archipelago, four threatened procellariiform species breed there still relegated to the most inaccessible places, mainly islets, marine rocks and coastal cliffs; including, as the most significant values, the endemic and critically endangered Balearic shearwater *Puffinus mauretanicus* and the largest populations of European storm-petrels *Hydrobates pelagicus* in the Western Mediterranean (Madroño et al. 2004).

In this study, we evaluate the effect of light pollution as a source of mortality for fledglings of the three most abundant petrel species breeding on the Balearic Islands: the critically endangered Balearic shearwater, as well as the regionally endangered Scopoli's shearwater *Calonectris diomedea* and European storm-petrel (Madroño et al. 2004). These three species differ in size, abundance, breeding period and distribution among islands. In addition, Balearic Islands constitute a different scenario from other locations where fallout has been studied (e.g. Azores, Canary Islands, Hawaii, La Reunion Island or Phillip Island), as light pollution levels are higher than reported elsewhere (maximum radiance value: 197.3 nW/sr*cm^2 vs. 103.6 nW/sr*cm^2 on Tenerife Island –the highest value where fallout has been studied; see Table 2 in Rodríguez et al. 2014 for a comparison) and distribution of colonies are mainly located on coastal areas. In this regard, petrel colonies can be located inland on typical oceanic islands, such as Azores, Canaries, Hawaii or La Reunion. Thus, Balearic Islands are an exceptional scenario to study a crucial conservation question in the human-wildlife conflict of light pollution and seabirds. It has been proposed that fledglings could be attracted to lights once they successfully reach the ocean (Podolski et al. 1998). It means that fledglings from dark colonies are also vulnerable to light attraction because they can be attracted back to land (Troy et al. 2011, 2013). However, the proportion of fledglings attracted in this way does not seem to be considerable according to GPS-tracked and banded birds from known colonies at the Canaries (Rodríguez et al. 2015). Given the coastal distribution of the breeding colonies at Balearic Islands (mainly on islets and marine rocks), the majority of birds grounded by lights must have flown over the sea. Thus, if the proportion of affected birds in relation to annually produced fledglings is high, it means that fledglings can be attracted back to land lights. On the other hand, if the proportion of affected birds is low, the numbers of birds attracted back to land would not be significant for the phenomenon of petrel attraction to artificial lights.

Our specific aims are: 1) to estimate the proportion of fledglings grounded by artificial lights with respect to the total fledglings annually produced by the population; 2) to study body condition and fatality in relation to rescue date; 3) to calculate the radius of light pollution impact by assigning birds to the nearest breeding colony and comparing with data coming from ringing programs conducted on two colonies of Scopoli's shearwaters; and 4) to evaluate light pollution levels in the breeding colonies proximities to quantify alterations of breeding habitats due to this emerging pollution.

Material and Methods

Study area

The Balearic Islands, western Mediterranean Sea, comprise four major islands (Majorca, Minorca, Ibiza and Formentera) and several islets and rocks. More than one million people inhabit the archipelago, the majority concentrated along the coast, and approximately 13 millions tourists per year visit the archipelago (IBESTAT 2014). According to the analyses of satellite imagery, light pollution levels have increased during recent years (de Miguel et al. 2014).

Species

The Balearic shearwater *Puffinus mauretanicus* is the most threatened seabird in Europe (1,750-2,125 breeding pairs, Sauleda 2006), the most critical threats being predation by introduced mammals and fishery bycatch (Arcos 2011). Other threats, including light pollution, have been mentioned in Balearic shearwater conservation action plan, but limited information regarding their effects on populations has been provided (Arcos 2011). In addition, some events of predation by peregrine falcons have been recorded at night at the breeding colonies, which could be related to an artificial increase of light levels (García 2009; Wynn et al. 2010).

The Scopoli's shearwater *Calonectris diomedea* is the largest and the most abundant of the Balearic procellariiforms (100-125 cm wingspan and around 11,000 breeding pairs). Some references indicate that this species is grounded by light pollution in some Mediterranean islands (Baccetti et al. 2005; Raine et al. 2007; Laguna et al. 2014), although no information on scientific literature is available for the Balearic Islands.

The European Storm-petrel *Hydrobates pelagicus* is the smallest petrel breeding on the Mediterranean basin (36-39 cm wingspan). The Balearic archipelago holds the largest populations in the Western Mediterranean (2,916-4,046 breeding pairs, Sauleda 2006). This species can be affected by light pollution in two different ways: 1) attraction and disorientation of juveniles (Laguna et al. 2014); and 2) increase of predation rates by gulls in light polluted colonies (Oro et al. 2005).

A small mixed population of Yelkouan shearwater *Puffinus yelkouan* and Balearic shearwater is breeding on Minorca. Despite several morphological and genetic studies, taxonomic status of these birds is controversial (see Arcos 2011; Genovart et al. 2012). For this reason, we considered all *Puffinus* fledglings as Balearic shearwater specimens.

Rescue and ringing campaigns

Data on rescued birds come from three wildlife rehabilitation centres located on the three main islands (Majorca, Minorca and Ibiza) and sponsored by the regional government (Consorci per a la Recuperació de la Fauna de les Illes Balears, Govern de les Illes Balears). The study period extends from 1999 to 2013. Birds were collected by the public or personnel of the wildlife rehabilitation centres and examined by qualified staff for identification, ringing, assessment of condition and health status, and release into the wild, if possible. Injured birds were admitted and held for rehabilitation or euthanized. In contrast to other islands where petrels are severely affected by lights (Telfer et al. 1987; Le Corre et al. 2002; Rodríguez and Rodríguez 2009; Fontaine et al. 2011; Rodrigues et al. 2012), no public dissemination of rescue campaigns is conducted by local administrations to mitigate light pollution mortality on the Balearic Islands. Thus, data presented here on the number of grounded birds should be interpreted as minimum numbers, as some birds could be found by people unaware of light pollution-seabird problem.

As part of a long-term programme for monitoring breeding success and recruitment rate of Scopoli's shearwaters, nestlings of two colonies (Illot Pantaleu, Majorca and Illa d'Aire, Minorca) are ringed at their nests before fledging. We used ringing data from these colonies to estimate the rate of birds grounded by lights. A total of 190 nestlings were ringed on Illa d'Aire in the 2002-2006, 2009-2010 and 2012-2013 breeding seasons. On Illot Pantaleu, 1,084 nestlings were ringed in the 2000-2009 and 2011-2012 seasons.

Impact on the populations

To roughly estimate the impact of artificial light attraction at fledging and compare with other studies, we followed formulas given by Le Corre et al. (2002). We first determined the total number of fledglings annually produced by the population of the three species. We multiplied productivity (proportion of pairs laying an egg that produced a fledgling) by breeding population size, taking into account the probability of reproduction skipping (Table 1). Then, we divided the number of annually grounded birds by the number of fledglings produced by the population for each species. Finally, we calculated 95% confidence intervals for the smaller estimated population sizes.

We used population size and productivity from literature (Table 1), and we assumed they were constant among years. Estimating breeding population size of burrow-nesting petrels is challenging and some of them could be overestimated (e.g. the European Storm-petrel; see Madroño et al. 2004). Some grounded fledglings could never be found by rescuers. Fledglings look for hiding places during daylight hours, could ground in or reach not-frequented places or may be unreported by unaware people. Thus, our estimates should be interpreted with caution and as minimal numbers. Despite constraints (i.e. assumptions on constant population size and productivity, and the presumably underestimated numbers of grounded birds), estimates give us a rough idea of the magnitude of the problem and allow comparison with other studies which follow the same methodology (See Table 2 in Rodríguez et al. 2014).

Environmental information and variables

Information on spatial distribution of species was taken from BioAtles, Govern de les Illes Balears (available at http://bioatles.caib.es). Resolution was based on a 1x1 km grid size. Light pollution levels were taken from a cloud-free composite of VIIRS nighttime lights corresponding to April and October of 2012 and produced by the Earth Observation Group, National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (available at http://ngdc.noaa.gov/eog/viirs/download_monthly.html). VIIRS imagery with a spatial resolution of 742 x 742 m and no saturation constitutes an improvement to the previous DMSP satellite imagery (Elvidge et al. 2013).

Geographical analyses to obtain distances from colonies to rescue location and light pollution levels of colonies and rescue locations were conducted in QGIS version 2.0.1 (Open Source Geospatial Foundation Project, http://qgis.osgeo.org). Because the majority of rescued birds were not ringed at their colonies, we assumed that birds were coming from the nearest colony, following Rodrigues et al. (2012). To determine light pollution levels at colonies we used centroids of 1x1 km square cells having a colony of at least one species. We report the single value of the pixel intersected with the centroids, but also the mean and maximum values in a 4 km radius buffer centred at the centroid of the 1x1 km cells representing a breeding colony.

Statistical analysis

To test the effect of rescue date (explanatory variable) on the status of birds (response variable with two levels; released vs. dead), we used generalized linear models (GLM) with binomial error structure and logit link function for each species. The significance of the model was assessed by a likelihood ratio test, comparing deviance with the null model (comprising only the intercept). We run Pearson's correlations to test for relationships between body mass and date of rescue for the Balearic and Scopoli's shearwaters (data on storm-petrel body mass were unavailable). To test for differences in distances to colonies and light pollution levels among species, we conducted linear models. Variables were transformed to meet normality and homoscedasticity assumptions. 'Distance to nearest colony' and 'light pollution level' were log (i.e. ln (x +1000)) and square root-transformed, respectively.

Statistical analyses were conducted in R version 3.0.3 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Magnitude, geographic and timing of fallout

A total of 304 fledgling birds were found stranded due to attraction to artificial lights on the Balearic Islands in the period 1999-2013. The most abundant species was the Scopoli's shearwater (199 birds), followed by the Balearic shearwater (66 birds) and the European storm-petrel (39 birds). The percentage of fledglings grounded by artificial lights was lower than 1% for the three species (Table 1). Despite of the lower breeding population size, the critically endangered Balearic shearwater was the most affected species. The highest number of grounded birds was reached in Minorca (147 birds), followed by Ibiza (92), Majorca (61) and Formentera (4). The birds were rescued mainly in the periods 13-20 October, 4-14 July and 20 August-5 September for

Scopoli's shearwater, Balearic shearwater and European storm-petrel, respectively, coinciding with the fledging season of each species (1st and 3rd quartiles; Fig. 1).

Mortality and body condition

Twenty-six (8.5%) out of 304 birds were fatally affected by lights. No differences in mortality frequency were detected between species ($\chi^2 = 3.364$, d.f. = 2, $P = 0.186$). Only the GLM explaining the relationship between probability to die and rescue date for Scopoli's shearwater was significant as compared to the null model (likelihood ratio test: $\chi^2 = 11.484$, $P < 0.001$) and it showed that probability to die increased with the fledging season (Estimate ± SE: 0.205 ± 0.053; $\chi^2 = 3.887$, $P < 0.001$). The remaining GLMs for the Balearic shearwater and the European storm-petrel were not significantly better than their respective null models (likelihood ratio tests: $\chi^2 = 0.004$, $P = 0. 949$ and $\chi^2 = 0.608$, $P = 0.435$, respectively). The body mass of Balearic and Scopoli's shearwater fledglings decreased with rescue date ($r = -0.762$, $P < 0.002$, n = 13; and $r = -0.501$, $P < 0.001$, n = 45, respectively).

Distances from rescue locations to colonies

Birds were rescued at a mean distance of 4,833 m from the nearest colony (median= 4,206, 1st and 3rd quartiles = 1,581 and 5,644 m, n = 303; Figs. 2 and 3). Mean distances were different between species ($F_{2, 300} = 5.438$, $P = 0.005$), Scopoli's shearwater being rescued at closer locations (4,219 ± 6,701 m, mean ± SD) than the other two species (5,943 ± 7,094 m for the Balearic shearwater and 6,075 ± 5,413 m for the European storm-petrel). However, information coming from Scopoli's shearwater ringings indicates they flew shorter distances. Only 10 out of the 1274 Scopoli's shearwater fledglings ringed at their natal colonies were recaptured, and all within a 4 km radius from colonies (eight and two birds from Pantaleu and Illa d'Aire colonies respectively; see inset in Fig. 2). In addition, one ringed Balearic shearwater fledgling was recovered at a distance of 1,581 m from its natal colony, Mola de Maó, Minorca.

Light pollution levels at rescue locations and colonies

Light pollution levels at rescue locations ranged between 0.2 and 123.4 nW/sr*cm^2 (mean= 24.6, median= 21.0, 1st and 3rd quartiles = 5.2 and 38.1 nW/sr*cm^2, n = 303) and no significant differences were detected between species ($F_{2, 300}$ = 2.522, P = 0.082; Figs. 2 and 3). In general, colonies were exposed to low light pollution levels, only 2-4 out of the 10-15 colony buffers (depending on species) showed mean radiance values higher than 1 nW/sr*cm^2. However, a higher proportion (30-47%) of colonies showed areas with high levels of light pollution, i.e. higher than 10 nW/sr*cm^2, within a 4 km radius (Table 1). One hundred and ninety-eight birds (65% out of the total fallout) were assigned to colonies exposed to radiance values higher than 10 nW/sr*cm^2 within a radius of 4 km. No significant differences were observed between the light pollution levels at colonies of the three species (Mean values: $F_{2, 34}$ = 0.163, P = 0.850; Max. values: $F_{2, 34}$ = 0.471, P = 0.629; log-transformed variables).

Discussion

Magnitude of fallout

Our study provides baseline information on the light-induced mortality of three petrel species on the Balearic Islands, including the critically endangered Balearic shearwater. The numbers reported here are low in comparison to those from other islands and species, where thousands of fledglings are involved in a single fledging season (e.g. Day et al. 2003; Fontaine et al. 2011; Rodríguez et al. 2012b). This figure seems to be general in the Mediterranean Sea where low affection rates have been recorded (Baccetti et al. 2003; Raine et al. 2007; Laguna et al. 2014). Distribution of colonies seems to play a crucial role in the fallout numbers. In the Balearic Islands, as in many other Mediterranean islands, breeding colonies are mainly located on islets and rocks offshore or on coastal sectors at low altitudes, and thus, many fledglings successfully reach the ocean. According to this, petrel fledglings are not massively attracted back to land lights (but see Troy et al. 2013). A similar case occurs with other species mainly breeding at coastal sectors, such as the wedge-tailed shearwater *Ardenna pacifica* on La Reunion, Indian Ocean (Le Corre et al. 2002), or the short-tailed shearwater *Ardenna tenuirostris* on Phillip Island, Australia (Rodríguez et al. 2014), where a small proportion of annually produced fledglings are grounded by lights.

However, on islands where fledglings from inland colonies must fly over cities to reach the ocean, the rate of grounded birds by lights is higher (Rodríguez et al. 2014).

Mortality and body condition

Without human intervention (rescuing), all grounded birds would die because most probably any would have reached the sea for themselves (Le Corre et al. 2002). Mortality rate at rescue was similar to other studies conducted elsewhere, which ranges between 4 and 14% of rescued birds (Rodríguez et al. 2014). However, we have to note that light-induced mortality is underestimated because 1) an unknown number of the grounded birds are never found, and 2) rescue campaigns based on the collaboration of the general public are biased toward the collection of live birds, i.e. lay people do not report (or collect) dead birds (Podolski et al. 1998; Rodríguez et al. 2014). Thus, if an active rescue patrol for dead and live birds had been conducted in the Balearic Islands, the mortality rate would have increased as recorded for the Newell's shearwater *Puffinus newelli* or the short-tailed shearwater *Ardenna tenuirostris* (assuming no species-specific differences in attraction to light; Ainley et al. 2001; Rodríguez et al. 2014).

As previously recorded for Cory's shearwaters *Calonectris borealis* (Rodríguez et al. 2012a), we found that both the probability of releasing back to the wild a rescued bird and the body mass decreased with the date of admission at the rehabilitation centre. Given that body mass at fledging seems crucial for recruitment into the breeding population (Mougin et al. 2000), an effort should be made to rescue the birds as soon as possible reducing the probability of dying and improving their fitness. In this sense, rescued fledglings of the endangered Newell's shearwater are admitted for rehabilitation and feeding if they fall below a minimum body mass threshold (Griesemer and Holmes 2011). A similar action could be undertaken with those birds rescued late at the fledging season, especially for the critically endangered Balearic shearwater.

Distances and light pollution levels

The distances observed in the Balearic Islands are similar to those reported for GPS-tracked Cory's shearwaters on Tenerife, Canary Islands (mean distance = 5,108 m for birds with a known origin; Rodríguez et al. 2015), but longer than mean distance

(2,387 m) estimated in Sao Miguel, Azores (Rodrigues et al. 2012). The higher light pollution levels of the Balearic Islands and Tenerife could explain these differences, as the higher the intensity of light pollution the further away the birds are attracted from (Rodríguez et al. 2015). In addition, the higher spread distribution of colonies at Sao Miguel in comparison to the confined colonies on Balearic Islands could also explain the differences in distances.

In general, colonies showed low mean light pollution levels, but 30-47% of them were exposed to radiance values higher than 10 nW/sr*cm^2 (percentages vary on species; Table 1). That is a very conservative estimate of light pollution affection on colonies because of the cut-off points used: 1) more than a third of birds are grounded in areas with radiance values lower than 10 nW/sr*cm^2 (104 out of 304 found birds); and 2) 54% of birds were rescued farther away than 4 km from the nearest colony (163 out of 304 found birds). Despite this conservative threshold, colonies exposed to radiance values higher than 10 nW/sr*cm^2 were the main contributors to the fallout (65% of rescued birds were assumed to be born at these colonies), which points to the validity of our approach.

Finally, we should note that light-induced mortality is not limited to coastal cities. Fledglings can also be attracted to lights of ships or oil platforms, extending the problem of light pollution at sea (Wiese et al. 2001; Merkel and Johansen 2011; Glass and Ryan 2013). In this sense, the increase of recreational vessels and cruise ships, which are currently an important touristic resource for the archipelago, and oil-drilling plans of the Spanish Government around Balearic waters, will not only increase the mortality of birds by light attraction, but also due to the inevitable oil spills and marine litter from ships (Ronconi et al. 2014).

Recommendations and conclusions

Although numbers of birds grounded by lights are not high, reducing mortality by anthropogenic causes should be a priority for the management and conservation of these threatened species. To mitigate light-induced mortality and to have a better idea of its effect, we recommend establishing a rescue campaign during the fledging seasons, especially for the Balearic shearwater. Rescue campaigns should, at least, focus on the nearest urban areas to breeding colonies. Educational campaigns to make the general public aware of the economic, environmental and health consequences of light pollution should accompany rescue campaigns. Regional governments should legislate to preserve the natural night sky, reducing light pollution levels as low as possible, especially in the proximities of colonies. These measures would help to save limited economic resources, but also to preserve the natural and crucial fledging processes of nocturnal seabirds.

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Table 1 Affection levels of light pollution on annually produced fledglings and colonies for three petrel species on the Balearic Islands during the period 1999-2013.

Species	English name	Conservation status		Breeding population size[c]	Productivity	Probability of skipping	% of grounded fledglings (95% C.I.)	Light pollution levels at colo	
		IUCN[a]	National[b]					colonies with mean values > 1	colonies with max values > 10
Puffinus mauretanicus	Balearic shearwater	Critically endangered	Critically endangered	1,750-2,125	0.61[d]	0.26[d]	0.46-0.56 (0.381-0.733)	2	5
Calonectris diomedea	Scopoli's shearwater	Least concern	Endangered	10,000-11,000	0.42[e]	0.15[f]	0.34-0.37 (0.256-0.488)	4	7
Hydrobates pelagicus	European storm-petrel	Least concern	Vulnerable	2,912-4,046	0.50[g]	~ 0[h]	0.13-0.18 (0.093-0.265)	2	3

[a] BirdLife International (2015); [b] Madroño et al. (2004); [c] Sauleda (2006); [d] Oro et al. (2004); [e] Amengual and Aguilar (1998); [f] Aguilar et al. (2011); [g] Sanz- Tavecchia et al. (2008); [h] Sanz-Aguilar et al. (2008).

Figure 1 Frequency distribution of petrel fledglings found grounded in the Balearic Islands during the period 1999-2013 for the three species: Balearic shearwater *Puffinus mauretanicus*, Scopoli's shearwater *Calonectris diomedea* and European storm-petrel *Hydrobates pelagicus*.

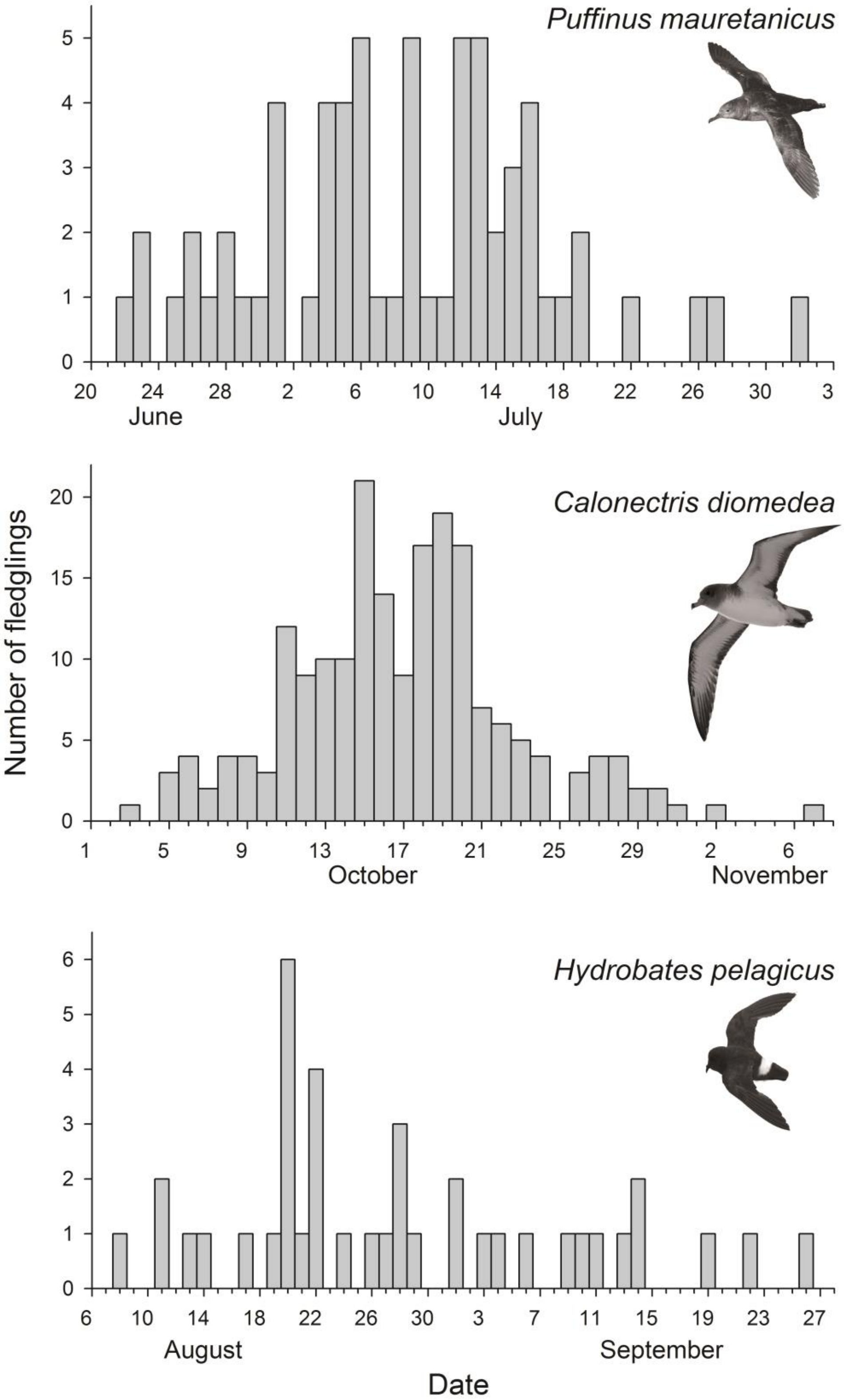

Figure 2 Histograms of distances and light pollution levels. Inset corresponds to distances from natal colonies to rescue locations of ringed Scopoli's shearwater. Distances correspond to the length in a straight line between rescue locations and the nearest colonies. Light pollution levels correspond to radiance values taken from a nocturnal satellite image produced by the Earth Observation Group, NOAA National Geophysical Data Center at rescue locations (see text).

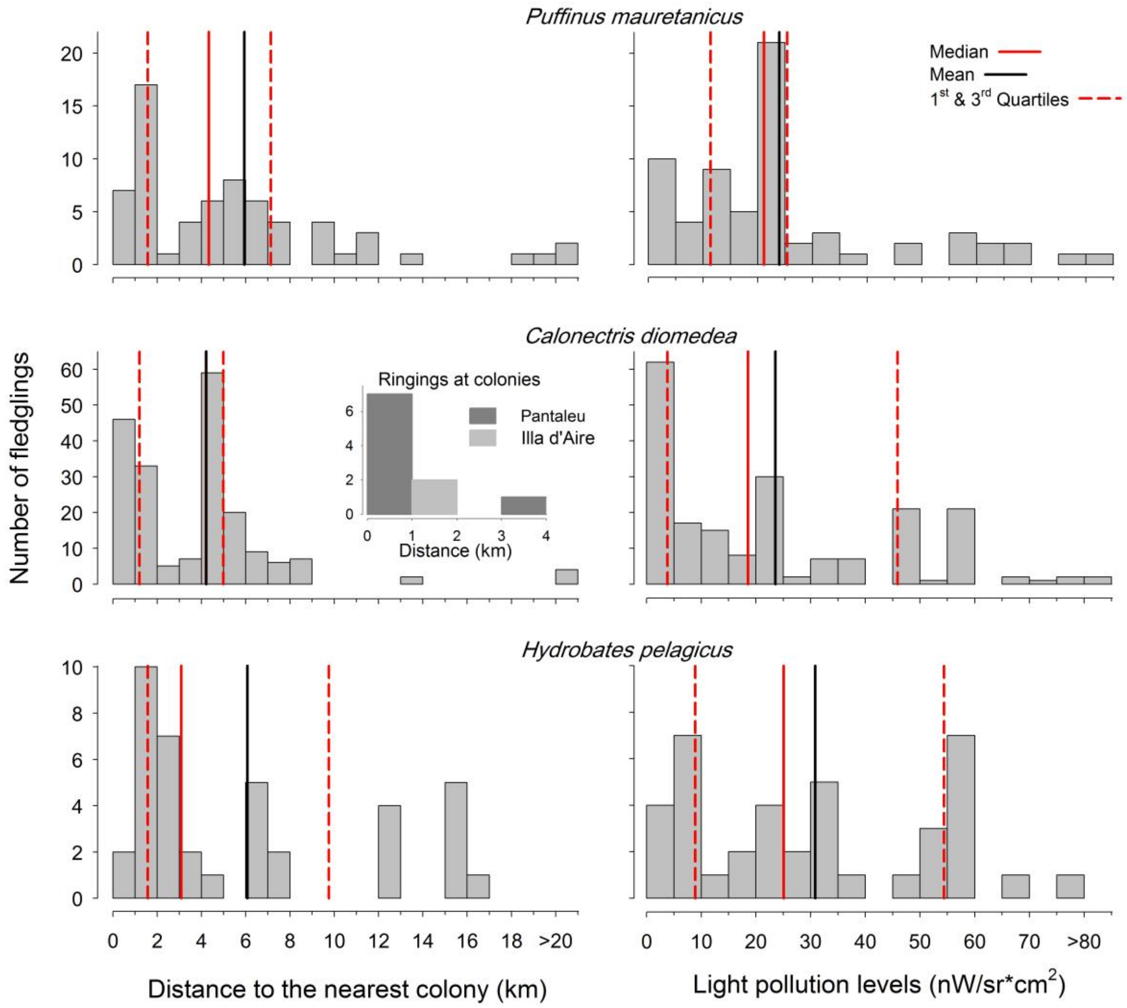

Figure 3 Rescue locations and breeding colonies of three seabird species on the Balearic Islands, Mediterranean Sea. Light pollution levels correspond to radiance values (nW/sr*cm^2) taken from a satellite image from National Geophysical Data Center. Lines represent a 4 km buffer around breeding colonies.