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Pedro Rodrigues, Christoph Aubrecht, Artur Gil, Travis Longcore & Chris Elvidge

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Remote sensing to map influence of light pollution on Cory's shearwater in São Miguel Island, Azores Archipelago

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Abstract Global economic and population growth increase the extent and intensity of artificial night lighting. From an ecological perspective, this is light pollution, which causes changes in reproductive physiology, migration and foraging of many species and ultimately leads to loss of biodiversity. Some seabirds are intimately linked with the light features of their environments because they are nocturnally active. We report light-induced groundings of Cory's shearwater (*Calonectris diomedea*) during a 2-year study (2008 and 2009) in São Miguel Island, in the Azores archipelago, and investigate the spatial correlation of locations of grounded birds with an annual composite of remotely sensed stable lights. Results indicate that 16.7% of fledglings are attracted to lights. The exposure of shearwater colonies in the study area to artificial night lighting is low overall. Four colonies account for 87% of the grounded birds. The distance each bird was found from the closest colony was best explained by the ratio of the satellite-measured light levels at the grounding spot to the light levels at the assigned colony of origin. These results demonstrate that satellite-observed nighttime lights are sufficient to assess risk to marine birds at the scale of oceanic islands and indicate their utility for monitoring the effectiveness of programs to manage lighting to reduce risk for these species and conducting global assessments of species vulnerability. To minimize the impact on Cory's shearwater and other marine birds, we recommend measures such as reduction and control of lighting intensity near colony locations, while continuing and re-enforcing rescue campaigns.

Keywords Light pollution · Marine birds · Remote sensing · Ground collection data · Azores Islands

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P. Rodrigues
CIBIO—Research Center in Biodiversity and Genetic Resources,
Department of Biology, University of the Azores,
Ponta Delgada, São Miguel, Azores, Portugal

C. Aubrecht
Foresight & Policy Development Department,
AIT Austrian Institute of Technology GmbH,
Vienna, Austria
e-mail: christoph.aubrecht@ait.ac.at

A. Gil
CITA-A (Azorean Biodiversity Group), Department of Biology,
University of the Azores,
Ponta Delgada, São Miguel, Azores, Portugal
e-mail: arturgil@uac.pt

T. Longcore
Spatial Sciences Institute,
University of Southern California,
Los Angeles, CA, USA
e-mail: longcore@usc.edu

C. Elvidge
National Geophysical Data Center (NGDC),
National Oceanic and Atmospheric Administration (NOAA),
Boulder, CO, USA
e-mail: chris.elvidge@noaa.gov

P. Rodrigues (✉)
University of the Azores,
Rua da Mãe de Deus, Apartado 1422,
9501–801 Ponta Delgada, Azores, Portugal
e-mail: pedrorodrigues@uac.pt

Introduction

Global economic development and population growth, especially as manifest in the extent of human habitation, entail a considerable increase in artificial lighting, both in terms of

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spatial extent and intensity, for infrastructure such as buildings, roadways, harbors, and airports. Significantly altering the natural environmental conditions, this form of pollution (called "ecological light pollution") causes deleterious effects on the behavioral and population ecology of organisms in natural settings (Longcore and Rich 2004). Some of the physiological, epidemiological and ecological consequences of this type of pollution were described by Verheijen (1985), Rich and Longcore (2006), and Navara and Nelson (2007).

Petrels and shearwaters (Family Procellariidae) are known to be very sensitive to artificial lights (Imber 1975) because they commonly attend breeding colonies at night. Artificial lights can attract and disorientate birds (Verheijen 1981; Longcore and Rich 2004; Poot et al. 2008), particularly fledglings during their first flight to the sea, and many of them thus fall to the ground with fatal injuries, are killed by predators or die of starvation (Le Corre et al. 2002; Miles et al. 2010). Two explanations are available for this attraction: (i) The artificial lights can lead to incorrect visual orientation since the first-time navigation to the sea at night depends on visual cues given from moon and star light (Telfer et al. 1987). (ii) Petrels and shearwaters feed on bioluminescent squids, and inexperienced birds tend to search for lights (including artificial lights) to improve their chance of getting a meal (Imber 1975; Klomp and Furness 1992; Montevecchi 2006). In addition, lights can have adverse effects at nesting colonies. Oro et al. (2005) report the increase of predation rates on storm-petrel (*Hydrobates pelagicus*) by yellow-legged gulls in areas of increased night lighting.

Many petrels and shearwaters have undergone substantial population declines. More than 50% of these species are threatened, mostly due to the presence of introduced predators and the impact of commercial fisheries (BirdLife International 2000). Although many of these species breed on islands inhabited by humans, a limited but growing number of studies focus on the impacts of artificial lights on their ecology. In Hawaii, urban lights were responsible for a large mortality of petrels (Telfer et al. 1987; Ainley et al. 1997). On Réunion Island, light pollution has caused mortality for all breeding species of petrels (Jouanin and Gill 1967; Jouanin 1987; Le Corre et al. 1996, 1999). On Tenerife in Canary Islands, light-induced mortality rates are reportedly of concern for petrels and small shearwaters (Rodríguez and Rodríguez 2009), as also reported by Miles et al. (2010) for St. Kilda in the Outer Hebrides.

In the Azores, the attraction of Cory's shearwater to artificial lights has long been known, and since 1995 the regional government has arranged rescue and awareness campaigns. This protected species is the most abundant seabird species of the Azores and is not under threat. However, populations are restricted to the Atlantic and Mediterranean Sea and their breeding population has declined precipitously in recent years (Bolton 2001).

The aim of this paper is to report light-induced groundings of Cory's shearwater in São Miguel Island, the biggest island in the Azores archipelago, and relate these data to satellite-observed nighttime lights. Based on our results and a review of relevant literature, recommendations and actions are proposed to minimize the adverse effects of light pollution on Cory's hearwater and marine birds in general.

Material and methods

Study area

The Portuguese Autonomous Region of the Azores, a group of nine volcanic islands, is situated in the mid-north Atlantic Ocean (between 36°55′ and 39°43′ N and 25°01′ and 31°07′ W), 1,500 km from Europe and 1,900 km from North America (Fig. 1). São Miguel is the largest island at 759 km^2, and the most populous (approximately 140,000 inhabitants). Most people live and work around the coast resulting in significant development pressure on the environment. In the last 20 years this trend has increased considerably. The narrow littoral fringe of the Azores islands is one of the few land areas that offers potential for settlement, and Azoreans are strongly dependent upon the sea for income, communication, and trade. This explains the coastal location of major commercial facilities and employment opportunities, together with economic activities and population (Andrade et al. 2006).

Study species

Cory's shearwater (*Calonectris diomedea borealis*) breeds in Iberian Peninsula, Azores, Madeira and Canary islands (Cramp 1977; Granadeiro et al. 2006), and is the most abundant pelagic seabird in the Azores archipelago breeding along the coast of all islands (Monteiro et al. 1996a, b). Feio and Monteiro (1998) estimated the Azorean population of this species at >400,000 individuals. This number decreased by ~50% in 5 years, with even greater declines (~75%) on the island of São Miguel (Bolton 2001). This species attends breeding colonies from late February to late October, passing a pelagic winter mainly in eastern South American areas (Mougin et al. 1988; Monteiro et al. 1996a). Cory's shearwater is highly synchronized both within and between colonies, with laying from late May to early June, hatching in late July and fledging from late October to early November (Zino et al. 1987; Monteiro et al. 1996a; Granadeiro et al. 2006). Counts of birds gathering in rafts around colonies, awaiting the onset of darkness before coming ashore, are used to estimate population sizes (Mallet and Coghlan 1964; Van Impe 1981; Feio and Monteiro 1998; Bolton 2001).

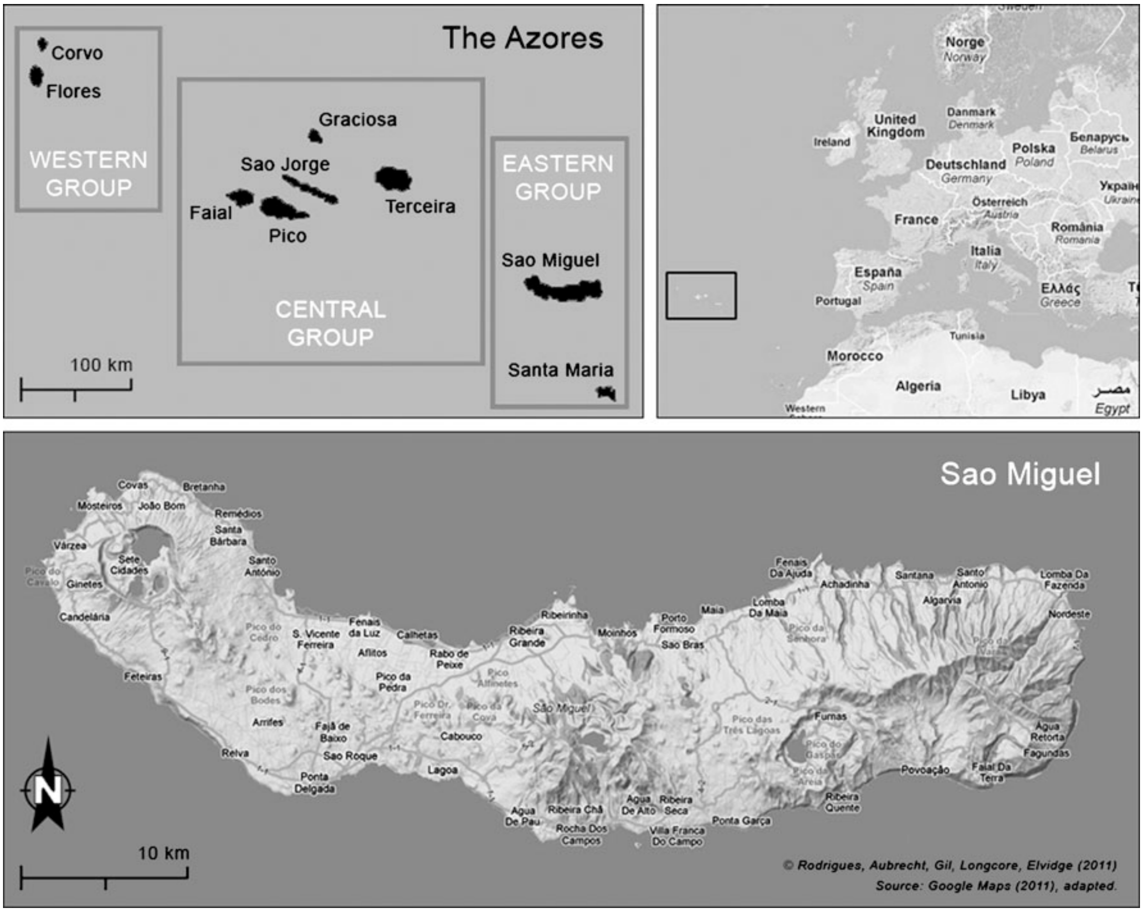

Fig. 1 Study area—the Azores Archipelago, a Portuguese autonomous region in the mid-north Atlantic Ocean

Grounding data

During the last 10 years the Regional Government has carried out awareness campaign called "SOS Cagarro" (http://soscagarro.azores.gov.pt/), which involves local media asking people to collect grounded birds and follow provided guidelines to release the animals safely (i.e., at the coast during daylight to avoid repeated distraction by artificial lights). Every night during the months of October and November, which is the period coinciding with the departure of juveniles from their nests for the first flight to the sea, the NGO "Amigos dos Açores" ("Friends of Azores"; www.amigosdosacores.pt) form several groups of volunteers that roam the streets and roads of São Miguel island to rescue grounded birds. For each bird (dead or alive), exact place and date are recorded.

During the months of October and November 2008 and 2009, 769 Cory's shearwaters were found grounded on streets and roads on São Miguel. Most of these birds were caught alive (85.79%) and these were released successfully. We imported location data for these records into GIS format for spatial analyses. Geographically, the grounding of birds was more intensive near the four major urban coastal areas, with >80% of the fallen birds: Vila Franca do Campo (38%), Ponta Delgada (21%), Ribeira Grande (13%), and Lagoa (10%).

Population surveys in 1996 and 2001 and the SOS Cagarro campaign records (2008/2009) show Cory's shearwater populations distributed evenly around São Miguel Island (Fig. 2).

Impact of light pollution in Cory's shearwater mortality

We assume that all grounded birds would have died without intervention of rescuers (Imber 1975; Le Corre et al. 2002). Grounded birds do not fly even if they are not injured, but rather seek a dark hiding place where they would probably die of hypothermia, starvation, predation or anthropogenic causes (e.g., traffic accidents).

To estimate the influence of light pollution on Cory's shearwater, we use methods applied for assessing light-induced mortality of petrels on Réunion Island (Le Corre et al. 2002) and Canary Island (Rodríguez and Rodríguez 2009).

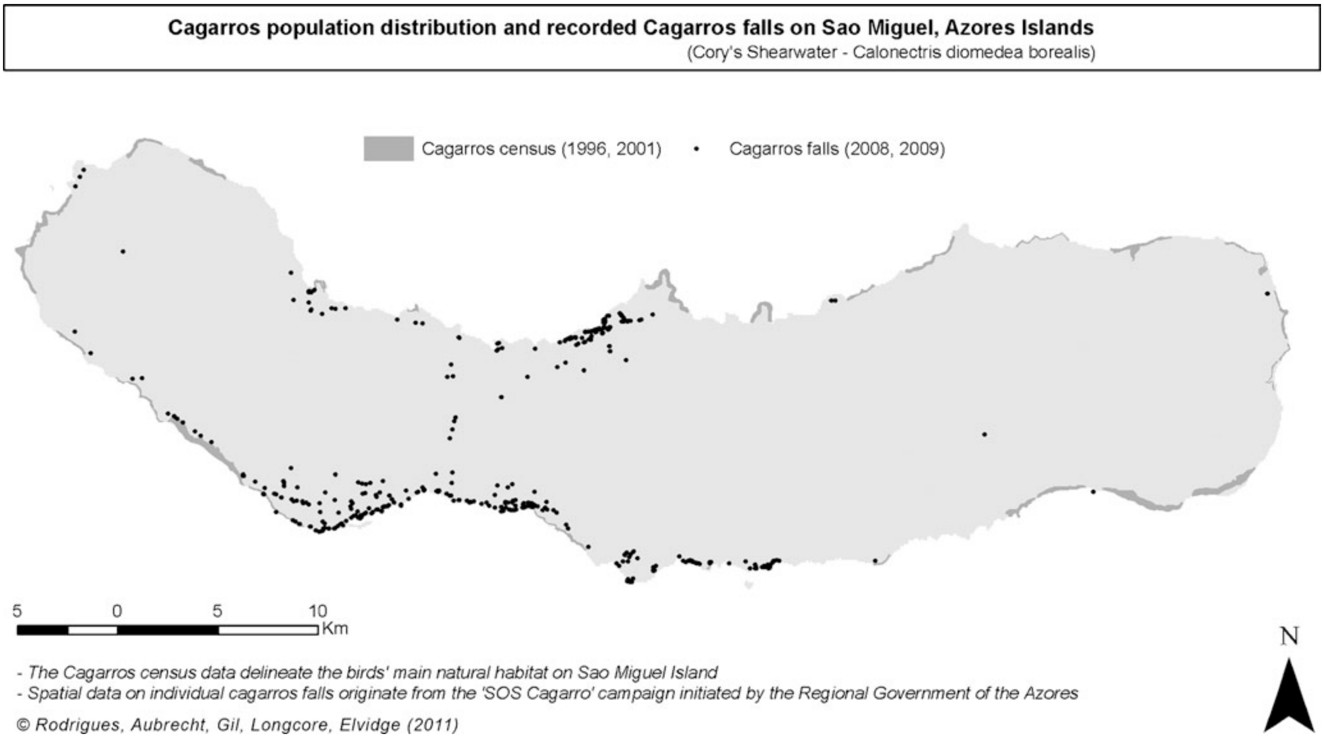

Fig. 2 Distribution of Cory's shearwater populations based on the 2001 census and the "SOS Cagarro" records on Sao Miguel Island

The proportion of fledgling lost by light attraction (PL) is calculated as:

$$\mathrm{PL}(\%) = \mathrm{FL}/\mathrm{FP} \times 100 \tag{1}$$

where FL is the total number of fledglings lost by light attraction and FP is the total number of fledglings produced annually by the population.

The FL value is difficult to estimate, so we use the most recent collecting data of 542 fledglings found grounded (i.e., 2009), knowing that the actual figure is probably much higher. FP values depend on the number of birds that successfully fledge (FS), on the adult population size (N in pairs) and on the proportion of breeders in the adult population (BP). Therefore the proportion of fledgling lost by light attraction (PL) is further stated as:

$$\mathrm{PL}(\%) = \mathrm{FL}/(N \times \mathrm{FS} \times \mathrm{BP}) \times 100 \tag{2}$$

For this study, we use the N of 9,828±1,413 (confidence interval [CI]=95%) bird pairs, based on the 2001 census (Bolton 2001). Because FS and BP are difficult to assess, we refer to figures published in recent literature. We use the FS value of 0.66, corresponding to the average breeding success without significant predation at colonies, estimated by Simons (1984), and the BP value of 50%, because some studies have shown that more than half of adult shearwaters at a colony may be non-breeders (Richdale 1963; Skira 1991; Monteiro et al. 1996a, b). Despite these sources of constraints and difficulties, these estimates approximate the magnitude of the effects of light pollution on the species.

Light pollution exposure mapping and impact assessment using satellite based nighttime earth observation

To map Cory's Shearwater exposure to artificial night lighting, we use an annual composite of cloud-free lights for the year 2008 from the most recent Version 4 DMSP-OLS Nighttime Lights data (i.e., composed of individual quality-proofed orbits from Defense Meteorological Satellite Program satellite F16; Elvidge et al. 1997, 2001; Quality criteria are described at www.ngdc.noaa.gov/dmsp/gcv4_readme.txt). We extracted the data for the entire Azores archipelago, eventually focusing on São Miguel Island. The final study area thus covers approximately 5,000 km² (northwest corner 38°N, 26°W, southeast corner 37.5°N, 25°W), i.e., also including a considerable buffer of surrounding ocean around the island, which has an area of 759 km^2. DMSP satellite sensors record areas larger than the immediate location of lighting sources on the ground. Nighttime lights data also include "artificial skyglow," i.e., light that is refracted or scattered by air and water molecules and suspended particles (atmospheric aerosol) caused by dust, pollen, salt from sea spray, and waste products from industry (Baddiley 2007). When dealing with ecological issues skyglow is a significant contributing factor of light pollution with very low light intensities already significantly altering natural environments (see Rich and Longcore 2006).

Cory's shearwater exposure to light pollution is analyzed by spatially overlaying the DMSP nighttime lights data and Cory's shearwater natural habitat information (spatial distribution from the 1996 and 2001 census). For comparison, we also look at the overall light pollution exposure of protected areas. The protected area delineation information originates from the Azorean Regional Secretariat for the Environment and the Sea ("S. Miguel Island Natural Park Creation and Regulation," according to Regional Legal Decree no. 19-2008-A). Additionally integrating the georeferenced SOS Cagarro records, we are able to move from exposure mapping to impact assessment and actually relate impact cases to light stress.

Exposure levels are determined for each colony by calculating the mean lighting intensity value [in digital numbers DN] (Table 1). Visible pixel intensity derived from DMSP-OLS is available in relative values ranging from 0 to 63 DNs rather than absolute values in Watts per square meter. Nighttime lights raster data are vectorized and intersected with census location data in a standard commercial Geographical Information System (ESRI ArcGIS) in order to come up with a mean lighting intensity value for each colony.

In a further step, we assign each SOS Cagarro record to the nearest colony by using GIS proximity analysis tools. Average values for the "lighting level at the grounding spot" (i.e., based on all records assigned to one colony), the mean and the maximum distances of grounding spots to the colony are calculated.

Table 1 Results of the spatial analysis—colony exposure to artificial night lighting and associated bird falls

Colony number	Total area (ha)	Census 1996	Census 2001	Light pollution exposure (DN)	Assigned bird groundings		Mean light at assigned bird groundings (DN)	Mean distance to colony (m)	Max distance to colony (m)
					Abs.	Rel.			
1	3.6	3,389	503	*14*	245	*31.9*	*23*	2,649	3,371
2	10.1	1,484	246	9	1	0.1	11	91	91
3	37.6	2,782	795	7	0	0.0	–	–	–
4	45.4	2,154	821	7	0	0.0	–	–	–
5	98.0	8,178	1,023	*13*	160	*20.8*	*37*	3,383	5,899
6	49.6	1,079	298	7	0	0.0	–	–	–
7	20.5	978	884	8	10	1.3	8	687	722
8	50.7	3,598	1,917	7	0	0.0	–	–	–
9	9.7	589	59	13	20	2.6	27	3,496	6,290
10	20.4	2,142	1,237	18	27	3.5	17	456	1,311
11	59.7	7,603	256	7	4	0.5	8	1,616	3,598
12	73.4	482	2,668	7	0	0.0	–	–	–
13	21.4	3,391	1,755	6	2	0.3	6	363	489
14	36.8	3,229	0	*14*	139	*18.1*	*28*	1,754	5,711
15	109.4	8,879	980	4	0	0.0	–	–	–
16	129.6	9,015	642	7	1	0.1	11	436	436
17	46.5	720	730	13	0	0.0	–	–	–
18	39.6	3,221	130	9	1	0.1	15	3,893	3,893
19	35,7	8,176	0	4	2	0.3	6	299	410
20	163.5	1,276	0	10	28	3.6	14	100	267
21	32.8	2,261	0	*34*	127	*16.5*	*47*	2,334	5,437
22	36.2	1,422	0	11	0	0.0	–	–	–
23	34.1	3,681	1,334	8	2	0.3	12	271	271
24	21.8	1,623	931	2	0	0.0	–	–	–
25	63.7	331	484	5	0	0.0	–	–	–
26	21.1	2,660	762	7	0	0.0	–	–	–
	1,270.88	84,343	18,455	9	769	100.0	30	2,387	6,290

With these data, we calculate summary statistics and build plausible mathematical models (multiple linear regressions) to explain the number of bird groundings and their distance from colonies. For example, we investigate explanatory variables such as the light measurement at the point of the grounding, the colony exposure to light, the ratio of light at the location of the fall to that at the colony, and colony size in relation to the distance each grounding occurred from a colony. These analyses are done with JMP 8.0 statistical software.

Results

Impact of light pollution on Cory's shearwater mortality

Our grounding data and population estimates indicate that 16.7% (±2.1, CI=95%), of the annually produced Cory's shearwater fledglings on São Miguel are attracted to lights each year.

Light pollution exposure mapping and impact assessment using satellite-based nighttime earth observation

Only eight of the analyzed 26 colonies show an average lighting intensity value greater than 10 DN and the mean value for all colonies is 9.65, i.e., overall light pollution exposure is rather low. One medium-size colony (approximately 33 ha) shows a strong outlier value featuring a DN of 34 (see Fig. 3b for a map showing colony exposure categories). This colony is closest to São Miguel's largest city (Ponta Delgada) on the southwest coast of the island. For this colony, no census is available for the year 2001, but 2,261 birds were counted in 1996.

Comparing the distribution of areas under legal protection status and the location of Cory's shearwater colonies, we find that 16 out of the 26 analyzed colonies are at least partly protected. This, however, just corresponds to about 30% of the total colony area. The mean nighttime light intensity (i.e., light pollution exposure) considering all protected areas of São Miguel is very low, i.e., with a DN of 7, it is even lower than the average value of the census-based colony areas. Only four of the 23 outlined protected areas feature an average light pollution exposure of DN> 10. There is again one outlier in the analysis (DN=53), i.e., a protected area in close proximity to the most exposed colony described above (i.e., near the city of Ponta Delgada).

An overlay of bird fall locations with the nighttime lights shows a distinct spatial correlation. We extracted night light intensity values from the DMSP data for each of the recorded bird fall locations (see Fig. 3c). The 769 collected data points which correspond to 458 distinct collection spots (i.e., up to 21 grounded birds were found at a single location) can thus be classified in three categories featuring rather low (DN<20), medium (DN 20–40), or high (DN>40) exposure to artificial night lights. More than 80% of the birds found stranded on the ground were collected in areas of medium or high light pollution (medium 61%, high 23%). Comparing those exposure values to the previously derived colony exposure levels, we see large differences, i.e., the mean exposure value at the grounding spots (normalized by the number of birds found at one location) is 30 compared to the previously derived mean light intensity value of 9 for all colonies (see Table 1).

Most of the records (87%; 671 birds collected at 398 locations) are spatially assigned to just four colonies. These four are all amongst the five colonies most exposed to artificial night lighting (marked in italics in Table 1). Fallen birds were still collected more than 5 km away from those colonies, whereas the average distance is 2.4 km. The mean lighting exposure at the bird-fall spots is significantly higher than at the colonies, on average we find a value increased by 50%.

The explanation of the distance that birds were found from colonies was a ratio of the light exposure at the site of the fall to the light level at the colony (r^2=0.19; $F_{1,767}$=183.3; p< 0.0001). The light exposure at the grounding location was also a significant explanatory variable (r^2=0.15; $F_{1,767}$; p< 0.0001), but was outperformed by the exposure ratio. At the colony level, the mean distance that birds were located from colonies was also best explained by the exposure ratio of the grounding site to the colony (r^2=0.42; $F_{1,13}$=9.72; p< 0.008), as was the maximum distance birds were found from each colony (r^2=0.45; $F_{1,13}$=10.5; p<0.006). Notably, colony size (1996 data) had an extremely small but significant influence on the distance that birds were found from it (r^2=0.078; $F_{1,767}$=38.7; p<0.0001); however, this influence was far less than the ratio of lighting between the two locations.

Discussion

Artificial lighting has changed the nocturnal activities of many animals. Ambient light influences reproductive physiology, migration, foraging, and hence parental behavior of many species. Perhaps more than other vertebrates, birds are intimately and inextricably linked with the light features of their environments (Farner 1964). A great variety of petrels and shearwaters species are attracted by lights (Imber 1975), but this phenomenon has been studied in detail only in few places such as Hawaii (Reed et al. 1985; Telfer et al. 1987; Ainley et al. 1997; Podolsky et al. 1998), Réunion Island (Le Corre et al. 2002), Canary Islands (Rodríguez and Rodríguez 2009) and Outer Hebrides (Miles et al. 2010). Although the

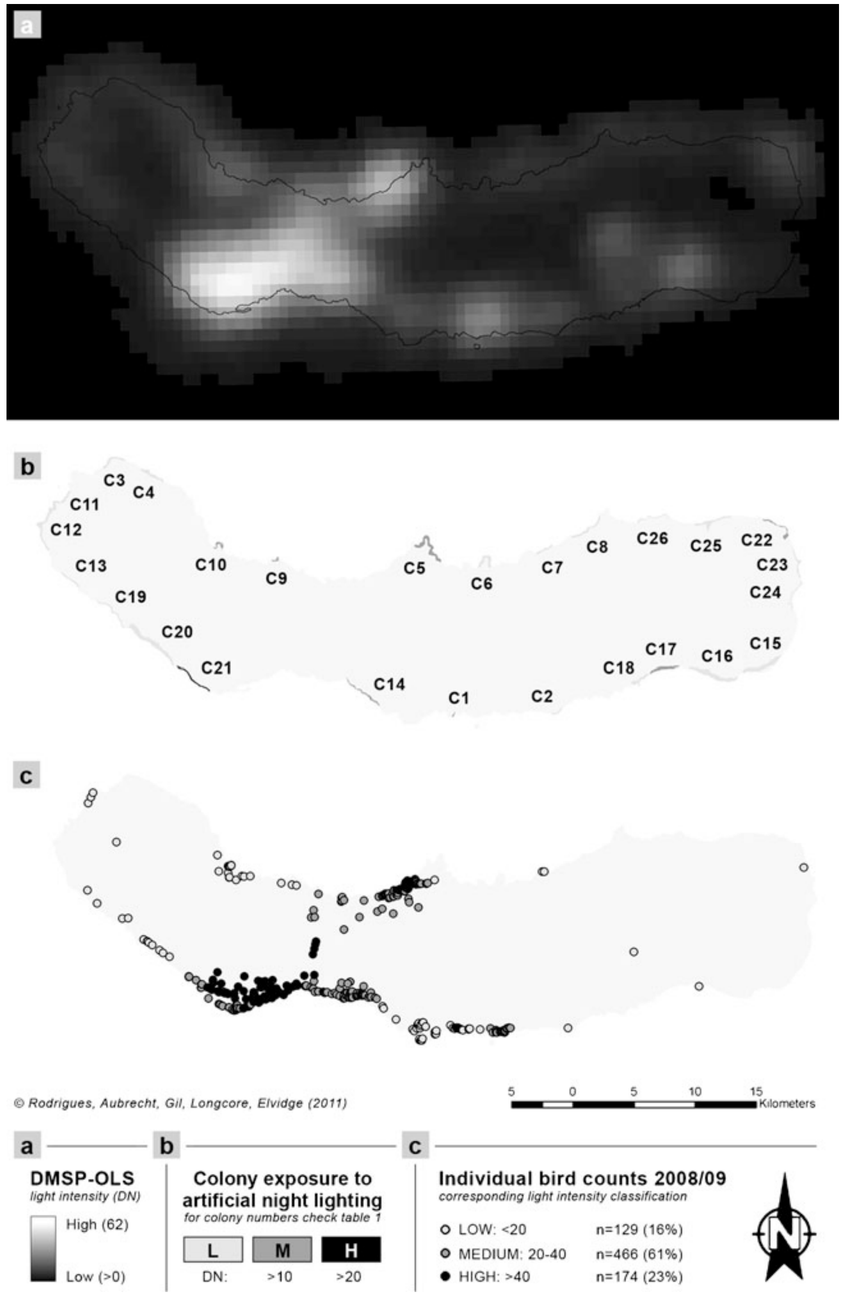

Fig. 3 **a** Satellite-derived image of artificial night lights (DMSP); **b** Cory's shearwater natural habitats (census 2001); **c** the georeferenced "SOS cagarro" records

majority of these studies involved different species, similarities to our work do exist. All of them correlate positively the increase of grounded birds with brighter artificial lights; the geographic distribution of the falling birds depends on urban and industrial areas in relation to the distribution of breeding colonies, mainly on coastal cities.

We estimated that around 17%, of the Cory's shearwater fledglings produced annually were affected by attraction to lights. This estimate is based on the assumption that in 2 years' study all the grounded birds were rescued. This is probably false because numerous grounded birds may have been killed and never been found, and others may have been found by unaware persons and let loose. In our study, we only take into account the months of October and November because this period coincides with the departure of juveniles from their nests for the first flight to the sea, but probably few other birds may have grounded in other months. Thus there are probably more losses of birds due to light attraction than we estimate. However our rough estimation provides valuable information relevant to the population dynamics of this protected species. In São Miguel Island, the PL value for the Cory's shearwater was rather low compared to the results for the same species in a similar study on the Canary Islands (Rodríguez and Rodríguez 2009), presumably due to the major colonies on

São Miguel having rather low exposure to light, which is confirmed by satellite images (see Fig. 3).

The major innovation of our study is the inclusion of the nighttime remote sensing imagery, which enables relating ground data records with light intensity in a consistent and spatially extensive way. Even though at this point the digital numbers from the "stable lights" satellite data cannot be directly transferred to brightness values (e.g., lux) on the ground, the data give an indication of patterns of varying intensity. Radiance calibrated lights products are not yet operationally available (see more information in the study of Elvidge et al. 1999). Analyzing 26 colonies in total we came to the conclusion that the vast majority of grounded birds records can be assigned to just four of these colonies. The mean lighting exposure at the grounding spots is significantly higher than the exposure at the colony locations. Bird falls were also recorded in greater distances to the respective colonies when fall locations were bright, and especially when they were bright relative to the nearest colony. This attraction from a colony location to a brighter location is consistent with other studies of attraction of organisms (Frank 2006; Salmon 2006). Shearwater colonies that were already experiencing high levels of artificial light were closest to bird fall locations that had greater average light exposure than colonies with lower light exposure. Some of this may be an artifact of assigning each bird to the closest colony, but only 91 of 769 (11.8%) birds were found at a location with lower light exposure than the nearest colony.

Taking into account the results of this study, there is an urgent need for developing effective mitigation measures to reduce the impact of artificial lights on birds. First, although we have identified the ratio of colony light exposure to surrounding areas as an important factor, making colonies brighter is not a solution because of the other adverse affects this would entail (e.g., increased predation; Oro et al. 2005; Riou and Hamer 2008; Keitt et al. 2004). Mitigation measures should include the use of light shielding, particularly in sites that attract more birds. A study carried out in Hawaii has shown that light shields, used to avoid upward radiation, decrease the attraction of Newell's shearwater (*Puffinus newelli*) by nearly 40% (Reed et al. 1985). An additional important proactive conservation measure would be the reduction of artificial light near colonies and an explicit restriction during the peak of fledging. Probably the best way to significantly reduce the mortality related to light attraction is however of responsive nature, i.e., reinforcing rescue campaigns. More than 85% of the fallen birds considered in our study were caught alive and successfully released, so a major effort should be made during the fledging peak period whereby increasing spatial coverage of these campaigns will undoubtedly increase the chance of grounded birds being found.

Furthermore, there is a significant need for the implementation of more awareness campaigns, not only in media but also in schools, to inform the public of the attraction of birds to light and its consequences. At last, there is a need to establish monitoring programs in order to quantify any population change due to light attraction and long-term studies of the biology and behavior of Cory's shearwater and other species that are known to be affected by lights. Improving conditions assumingly caused by law-enforced management activities against light pollution were observed on the island of Oahu in the Hawaiian archipelago in a satellite based analysis of trends of lighting impact on coral reefs (Aubrecht et al. 2009), so standardized methods are available for such monitoring.

Conclusions

Our study shows that light pollution affects negatively almost 20% of the Cory's shearwater fledglings, mainly on colonies close to high levels of artificial light. The use of nighttime remote sensing imagery was an important innovation on this type of study and given the global coverage, spatial and temporal resolution, and consistent nature of the DMSP nighttime lights data, the methods and analyses developed and carried out in this project for the island of São Miguel are easily transferable to other places. Depending on ground data availability, the next steps can include time series analysis, i.e., monitoring the trends in lighting impact on marine birds, and comparison of different geographical regions, such as extending the analysis to the whole of Macaronesia. The application of several mitigation measures could reduce the impact of artificial lights not only on this species but also in all the other marine species.

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