25 years of light-induced petrel groundings in Reunion Island: Retrospective analysis and predicted trends

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25 years of light-induced petrel groundings in Reunion Island: Retrospective analysis and predicted trends

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ABSTRACT

Artificial lights are known to induce mass mortality of petrels. This study analyzes this phenomenon in Reunion Island, where four species are impacted: the endemic Barau's petrel (*Pterodroma baraui*) and Mascarene petrel (*Pseudobulweria aterrima*), the tropical shearwater (*Puffinus bailloni*) and the wedge-tailed shearwater (*Ardenna pacifica*). 40,036 birds were found grounded between January 1996 and December 2021, most of which were fledglings. Spatial distribution of groundings matched with the distribution and intensity of light pollution. With a mark and recapture method, we estimated that at least 3.93 % of Barau's petrels fledglings are affected by light-induced groundings each year. This method was also used to estimate Barau's Petrel population around 33,000 breeding pairs. Time series analyses showed strong positive trends of the number of groundings for all species, which were positively correlated with the intensity of light pollution. All species showed a seasonal increase in groundings coinciding with their fledging periods. Interannual variations of Barau's petrel and wedge-tailed shearwater groundings were explained by moon phase at their fledging peaks. We built statistical models to explain year-to-year changes in the number of groundings for each species, and used them to predict the number of groundings in the next decades. We predicted that up to 87,000 petrels may be found grounded from 2022 to 2050 if nothing is done to reduce light pollution. These results and predictions underline the urgent need to strengthen the rescue campaign and to implement strong light reduction measures.

1. Introduction

Electrical lightning development, together with population growth and the extension of urban areas, has led to massive light pollution, a major alteration of the nocturnal environment (Longcore and Rich, 2004; Gallaway et al., 2010). Expanding both in area and in wavelengths range (Hölker et al., 2010a), light pollution is one of the most rapidly increasing anthropic perturbations (Cinzano et al., 2001). Numerous negative effects on biodiversity have been documented (Hölker et al., 2010b; Sanders et al., 2021), one of the

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most striking being mass mortality events of insects, turtles and birds caused by disorientation or attraction by artificial lights (Sanders et al., 2021).

Seabirds are one of the most threatened group of birds, because of multiple threats occurring at sea and on land (Dias et al., 2019). In particular, the Order Procellariiformes shows the highest proportion of threatened species (Rodríguez et al., 2019). Among them, petrels and shearwaters (hereafter 'petrels') nest in burrows and are mainly nocturnal at their breeding places, making them highly sensitive to light pollution when they commute from their colonies to the sea. Artificial lights can disorientate the birds and make them fall on urban areas, where they are unable to fly away. This phenomenon, termed 'grounding', affects mostly fledglings during their first flight to sea. If not rescued, grounded birds die from injuries, starvation or predation (reviewed in Rodríguez et al., 2017b). At least 62 species of petrels are affected by light-induced groundings around the world (Rodríguez et al., 2017b; Silva et al., 2020).

Reunion Island is the only oceanic island where two endemic petrel species are known to breed: Barau's petrel (*Pterodroma baraui*), classified as endangered, and Mascarene petrel (*Pseudobulweria aterrima*), classified as Critically Endangered (Virion et al., 2021). Two other petrels also breed on the island: tropical shearwater (*Puffinus bailloni*) and wedge-tailed shearwater (*Ardenna pacifica*), both found in Pacific and Indian oceans and classified as Least Concern (Faulquier et al., 2017). All four species are impacted by light-induced groundings in Reunion island (Le Corre et al., 2002, 2003). In order to reduce mortality of grounded petrels, a continuous rescue campaign was initiated in 1996 by the Société d'Etudes Ornithologiques de la Réunion (SEOR), a local NGO committed to bird conservation. Each bird found and reported is cared for and released back to sea when possible. As petrel groundings are island-wide and happen all year round, birds are not searched by professionals but only found by the general public.

To date, only one study conducted by Le Corre et al. in 2002 has reviewed the impact of groundings on all four petrel species in Reunion island, based on the four first years of data collection. Since then, petrel groundings have dramatically increased on the island (Faulquier et al., 2017; Virion et al., 2021). Thus, there is a need to update this study and address the following questions: How have petrels groundings changed over the last 25 years and which factors explain these trends? How are these groundings spatially distributed? What is the proportion of fledglings affected by groundings? How will groundings evolve in the future?

2. Materials and methods

2.1. Study area

Reunion Island is a mountainous volcanic island located in the western Indian Ocean (21°S, 55°E), covering an area of 2512 km^2. Urban areas are mostly located in the coastal zone, while the inland is mainly covered by crops, forests and mountains (up to 3070 masl). Settled by humans since the seventeenth century, the island has recently seen its population increase tremendously, from 250,000 inhabitants in the 1950s to more than 850,000 in 2020. This growth is causing important changes in the environment, one of them being the increase of light pollution.

2.2. Data collection

A continuous rescue campaign was initiated in 1996 to reduce mortality of grounded petrels, by asking general public to report any petrel found grounded to the SEOR. Each bird reported is collected, examined, cared for and released when possible. The date and place of each grounding are recorded, as well as whether the bird has been successfully released or not. Some additional data are also collected when possible: the GPS point of the place of encounter (since 2015) and the age of the bird (fledgling or adult).

To build our dataset, we compiled all data collected by the rescue campaign from January 1996 to December 2021 regarding petrel light-induced groundings.

2.3. Groundings characteristics

2.3.1. Influence of light pollution on the spatial distribution of groundings

To analyze how the location of groundings is influenced by the distribution and intensity of light pollution, we compared it with VIIRS rasters of mean annual radiance, which are a convenient proxy to indirectly measure light pollution at large temporal and spatial scale (Elvidge et al., 2013, 2021).

2.3.2. Influence of moon phases

To analyze how moon phases influences the number of groundings, we retrieved the illuminated fraction of the moon at the date of grounding of each bird with the R package *suncalc* (0 corresponding to new moon and 1 to full moon), and analyzed the numbers of birds found grounded according to this variable.

2.4. Proportion of fledglings affected and population size estimates

We used a mark and recapture method on Barau's petrel to estimate the proportion of fledglings affected by groundings. We also estimated the total number of fledglings produced each year and the number of breeding pairs.

Two colonies of this species are monitored annually: Bras des Etangs on the Piton des neiges mountain since 2003, and Grand Bénare on the eponymous mountain since 2008. Barau's petrel breeding area is very small, all colonies are located far inland on these two mountains and no coastal colonies exist (See Appendix A). Thus, these two sites are assumed to be representative of all colonies of this species in terms of breeding success and light pollution exposure.

The breeding success (BS) was estimated at the two monitored colonies each year, by dividing the number of fledglings by the number of pairs which had laid an egg at the beginning of the breeding season. Fledglings were also banded at these two colonies just before they fledged (the number of fledglings banded each year being defined as BF). Each grounded bird reported to the SEOR was then checked for the presence of a band. We defined BFG as the number of banded fledglings found grounded each year, and FG as the total number of fledglings found grounded (See Appendix B).

Assuming that chicks banded at the two monitored colonies are representative of all Barau's petrel chicks in terms of risk of grounding, we calculated PFG, the estimated proportion of fledglings affected by groundings each year, thanks to this equation:

$$PFG = BF \div BFG \tag{1}$$

Based on the same assumption, we considered that the proportion P of banded fledglings found grounded (BFG) among all fledglings found grounded each year (FG) is equal to the proportion of all fledglings banded (BF) among the total number of fledglings produced that year (defined as NF):

$$P = BFG \div FG \quad = \quad BF \div NF \tag{2}$$

So we could estimate NF for each year:

$$NF = BF \times (FG \div BFG) \tag{3}$$

We also estimated the breeding population size (defined as BP for breeding pairs) using NF and the breeding success monitored on colonies (BS):

$$BP \times BS \quad = \quad NF \quad so \quad BP = NF \div BS \tag{4}$$

As PFG and BP are estimated for each year, we computed overall means with confidence intervals. These calculations were made for Barau's petrel only, because we had too few chicks banded at colonies for other species to perform analyses.

2.5. Temporal analyses

2.5.1. Time series

To explore the different factors that influenced the trend of the number of groundings since 1996, we constructed a monthly time series for each species by counting the number of birds found grounded each month from January 1996 to December 2020 (300 months in total). We excluded 2021 data from our time series, because light pollution data was not yet available for this year at the time of writing but needed for further analyses. We used the R function *stl* to decompose each time series into 3 components: the trend (long term trend of the annual number of groundings), the seasonality (seasonal changes of groundings repeating regularly each year) and the residuals (fluctuations neither explained by the trend nor the seasonality). We used a 12-months time window to compute the seasonality, as groundings usually follow an annual cycle corresponding to the breeding cycle of each species (Le Corre et al., 2002). We widened the time window to 48 months to compute the trend, in order to reduce the influence of year-to-year variations, and analyzed whether it was significant with the Mann-Kendall statistical test for trend.

2.5.2. Correlation between the trend and changes in light pollution

To explain the trend component of the grounding time series, we retrieved light pollution data in Reunion Island thanks to the annual means of radiance measured by DMSP and VIIRS satellite instruments (Elvidge et al., 2013, 2021; DMSP data collected by the US Air Force Weather Agency), harmonized following Li et al. (2020) to allow for a comparison over a long time series despite differences between these two sensors. We tested whether the trend component of each species' groundings was correlated with the change of light pollution with Kendall rank correlation tests.

2.5.3. Seasonality analysis

Fledglings being essentially grounded during their first flight to sea (Reviewed in Rodríguez et al., 2017b), the annual distribution of their groundings coincides with their fledging period. Thus, we defined the mean fledging peak date of each species by retrieving the mean peak date of fledgling groundings over 25 years, at the scale of the entire island or by regions when regional differences were noticed.

2.5.4. Influence of moon phase at fledging peak

For each species, we tested the correlation between moon phase at fledging peaks and the residuals of the time series, in order to check whether the fluctuations remaining unexplained by the overall trend and the seasonality can be explained by moon phases.

2.6. 2021–2050 projections

For each species, we explored the relationship between the annual number of birds found grounded and light pollution (expressed as the annual mean radiance on the island) and with the moon phase during the annual fledging peak (expressed as the illuminated fraction of the moon at this date). We built a generalized additive model (GAM) for each species with the annual number of birds grounded as the dependent variable, and light pollution and moon phase at date of mean fledging peak as predictors.

We used these models to predict the number of grounded birds from 2021 to 2050. To do so, we projected the two predictors on this period. The moon phases at annual fledging peaks were predicted with the R package *suncalc*. For projected light pollution, we explored 3 different scenarios. The first one projects an increase corresponding to a continuous development of artificial lights on the island without any restricting measures (the "business-as-usual" scenario), with a growth rate from 2021 to 2050 similar to that from 1996 to 2020. The second scenario models the implementation of regulation measures (the "regulation" scenario), corresponding to a growth rate of only 20 % from 2021 to 2040 followed by a plateau. The third scenario models the implementation of measures to drastically reduce artificial lightning on the island (the "reduction" scenario), by projecting a 30 % decrease between 2021 and 2050. This reduction would result in a level of light pollution in 2050 equivalent to the one measured in 2006.

3. Results

3.1. Global analysis

40,036 petrels were found grounded from January 1996 to December 2021 on Reunion island, among which 22,129 were tropical shearwaters, 17,276 were Barau's petrels, 566 were wedge-tailed shearwaters and 65 were Mascarene petrels. 88.2 % of these birds were successfully released. Grounded birds were mainly fledglings for Barau's Petrel (96.4 %), tropical shearwater (97.9 %) and wedge-tailed shearwater (67.0 %), but only 43.1 % of grounded Mascarene petrels were fledglings. The annual number of groundings has increased from 1996 to 2021 for the four species (Fig. 1): trend is significant for Barau's petrel ($\tau = 0.536$, $p < .001$) with a compound annual growth rate (CAGR) of 9.21 %; as well as for tropical shearwater ($\tau = 0.889$, $p < .001$, CAGR = 13.44 %); for wedge-tailed shearwater ($\tau = 0.653$, $p < .001$, CAGR = 14.53 %) and for Mascarene petrel ($\tau = 0.343$, $p < .05$, CAGR = 4.49 %). The increase is quite steady for tropical shearwater, while it appears more uneven for other species, with important interannual variations.

3.2. Groundings characteristics

3.2.1. Spatial distribution

Groundings were not evenly distributed on the island, and their main locations varied according to the species (Fig. 2). Most Barau's petrels and tropical shearwaters were reported in coastal cities in the north, west and southwest of the island, with the exception of the town of Cilaos which is far inland but gathers a very large number of Barau's petrel groundings. Wedge-tailed shearwaters were mainly found grounded on the northwestern and southern coast, and most Mascarene petrels were reported in the south and west of the island though a few were reported in Salazie in the northeast. The spatial distribution of most birds found grounded matches perfectly with the areas that are the most impacted by light pollution (Fig. 3). However, lots of birds are also found in inland towns showing moderate radiance levels, such as Cilaos and Salazie.

Overall, most of the grounded birds were found at very low altitudes (71.02 % at less than 100 m above sea level, see Appendix C.1), at short distances from the sea (58.98 % at less than 1 km from the sea, see Appendix C.2), and in highly light-polluted areas (71.62 % in locations with an average annual radiance of more than 20 nW/cm^2/sr, see Appendix C.3).

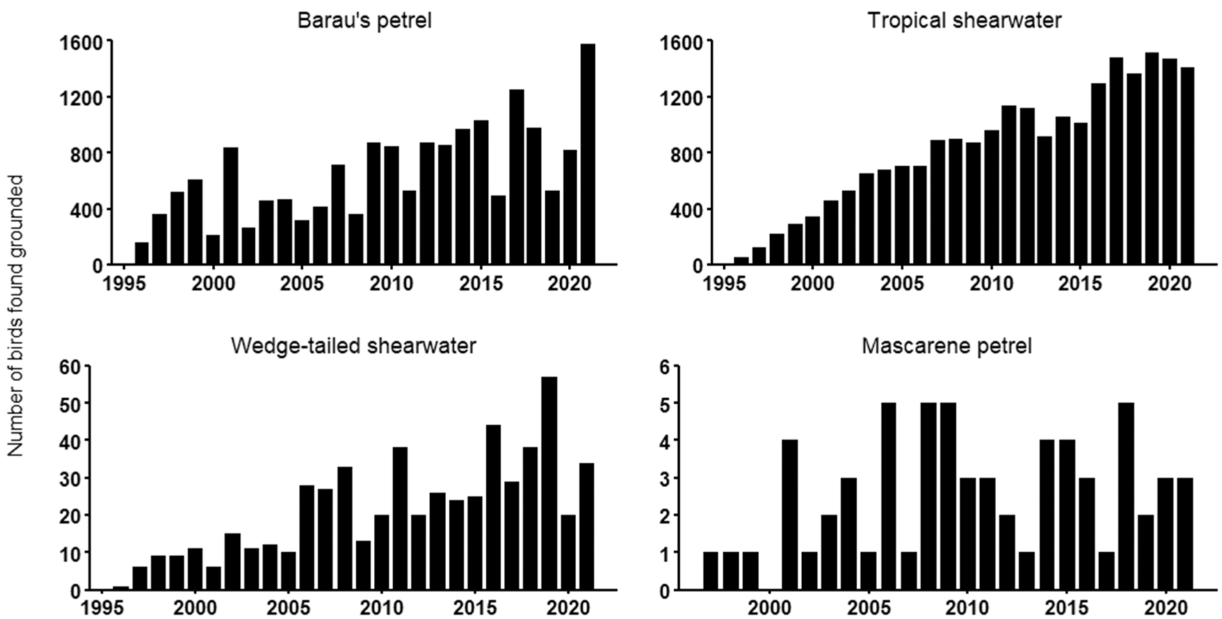

Fig. 1. Annual number of petrels found grounded on Reunion Island from January 1996 to December 2021.

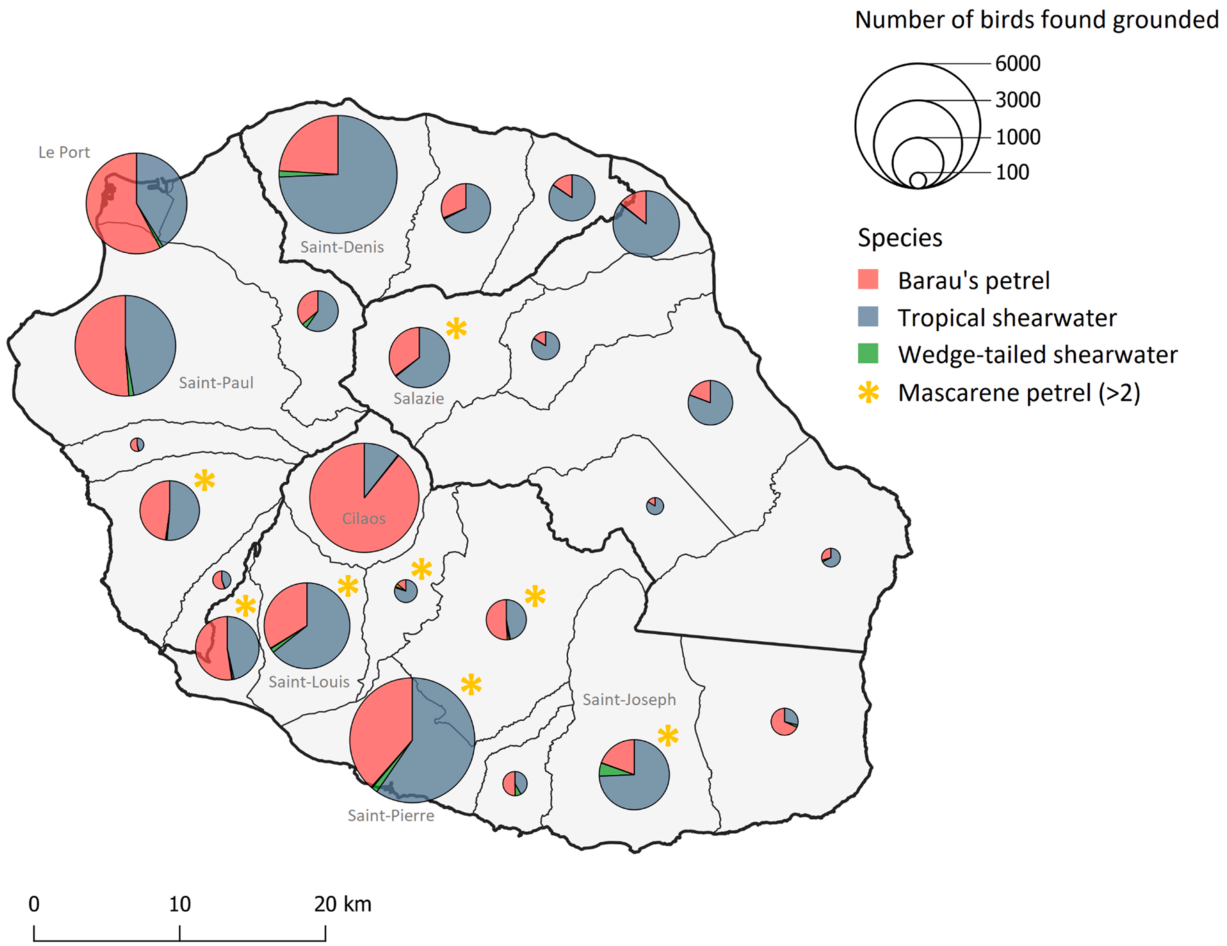

Fig. 2. Geographic distribution of petrel groundings on Reunion Island from 1996 to December 31, 2021. Notes: Bold lines show the different regions mentioned in the paper. Thin lines delimit municipalities. Municipalities with the most birds found grounded or mentioned in the paper are named in gray.

3.2.2. Influence of moon phases on groundings intensity

For all four species, Kendall correlation tests show that the number of birds found grounded by class of moon illumination is significantly and negatively correlated to this variable: $\tau = -1$, $p < .001$ for Barau's petrel; $\tau = -0.96$, $p < .001$ for tropical shearwater; $\tau = -0.56$, $p < .05$ for wedge-tailed shearwater; $\tau = -0.8$, $p < .01$ for Mascarene petrel (See Appendix D). For all species, most grounded birds have been found during new moons.

3.3. Proportion of fledglings affected and population estimates

From 2004–2019, 1 817 Barau's petrel fledglings were banded at breeding colonies and 40 of them were recovered among the 11,481 fledglings of this species found grounded during this period (See Appendix B). Using Eqs. (3) and (4), we estimated that 21,267 Barau's petrels fledglings were produced each year on average (sd = 15,324, 95 % CI [10 305, 32,229]), which corresponds to 33,019 breeding pairs (sd = 20,680, 95 % CI [18 235, 47,823]). On average, a minimal proportion of 3.93 % (sd = 2.13 %, 95 % CI [2.41 %, 5.45 %]) of Barau's petrel fledglings produced by the entire population were found grounded each year.

3.4. Temporal analyses

3.4.1. Time series

The decomposition of the time series of each species shows a positive trend of the number of groundings each year from 1996 to 2020, which is significant for Barau's petrel ($\tau = 0.605$, $p < .001$, compound annual growth rate (CAGR) = 15.44 %), tropical shearwater ($\tau = 0.846$, $p < .001$, CAGR = 14.00 %), wedge-tailed shearwated ($\tau = 0.608$, $p < .001$, CAGR = 13.11 %) and Mascarene petrel ($\tau = 0.18$, $p < .001$, CAGR = 4.07 %). Time series of each species also shows a very strong seasonal signal, and some residuals showing interannual deviations from the trend (Fig. 4).

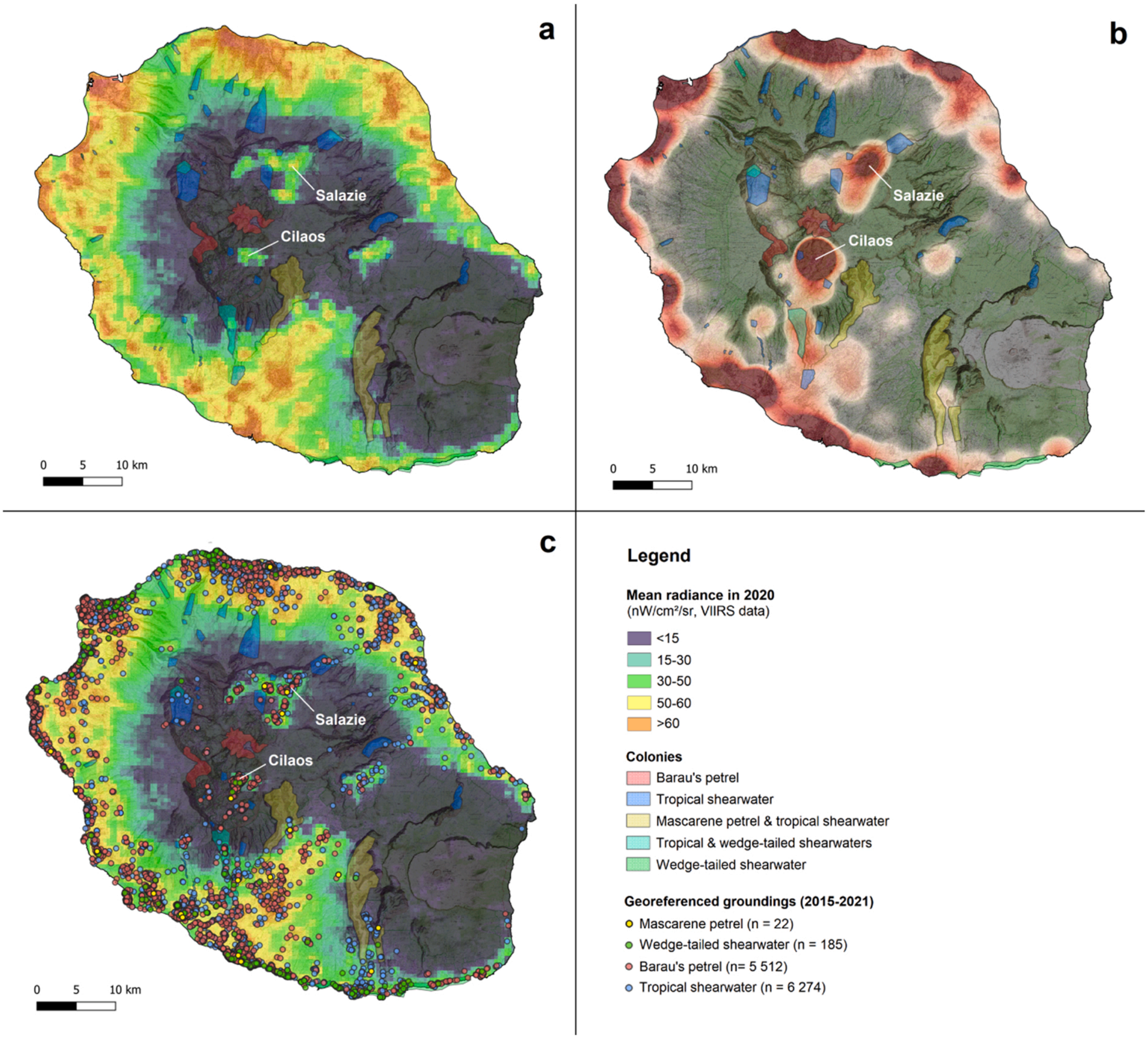

Fig. 3. 3a: mean radiance in 2020 (VIIRS data, Elvidge et al., 2013, 2021) and distribution of petrel colonies 3b: heatmap of georeferenced groundings from 2015 to 2021 (n = 11,993) and distribution of colonies 3c: georeferenced groundings from 2015 to 2021 (n = 11,993) and mean radiance in 2020 (VIIRS data). Data sources: UMR ENTROPIE; Gineste et al. (2017), Faulquier et al. (2017), Virion et al. (2021). Map data: IGN.

3.4.2. Explanation of the trend by light pollution

Harmonized DMSP and VIIRS data showed that the mean annual radiance on the island increased by 80 % between 1996 and 2020. Kendall correlation tests show that the trend component of time series shows a strong positive correlation with this variable for all species: $\tau = 0.71$, $p = 3.2\text{e-}08$ for Barau's petrel; $\tau = 0.69$, $p = 1.4\text{e-}07$ for tropical shearwater; $\tau = 0.6$, $p = 8.3\text{e-}06$ for wedge-tailed shearwater; $\tau = 0.33$, $p = .023$ for Mascarene petrel.

3.4.3. Seasonality analysis

The groundings of the four species have very distinct seasonal patterns (Fig. 5). Barau's petrel groundings happen seasonally in April (average grounding date: April 20 ± 5 days). Wedge-tailed shearwater groundings are very seasonal for fledglings, most of which are found in May (May 6 ± 3 days). Mascarene petrel groundings are quite seasonal for fledglings, only happening from February to April (March 1 ± 21 days), while adults are found throughout the year except in May and June, with a seasonal signal from December to February. Tropical shearwater is the less seasonal species, groundings occurring throughout the year with a wide seasonal peak from November to February, but we found regional variations in seasonality for this species (see Appendix E): the birds grounded in the northern and western parts of the island are mostly found around the end of December (respective average grounding dates: January 4 ± 16 days, December 29 ± 16 days), while those in the southern region are principally found around the end of January (January 26 ± 13 days). In the east region, most groundings are aggregated in two periods: in early December (December 3 ± 36 days) and, to a

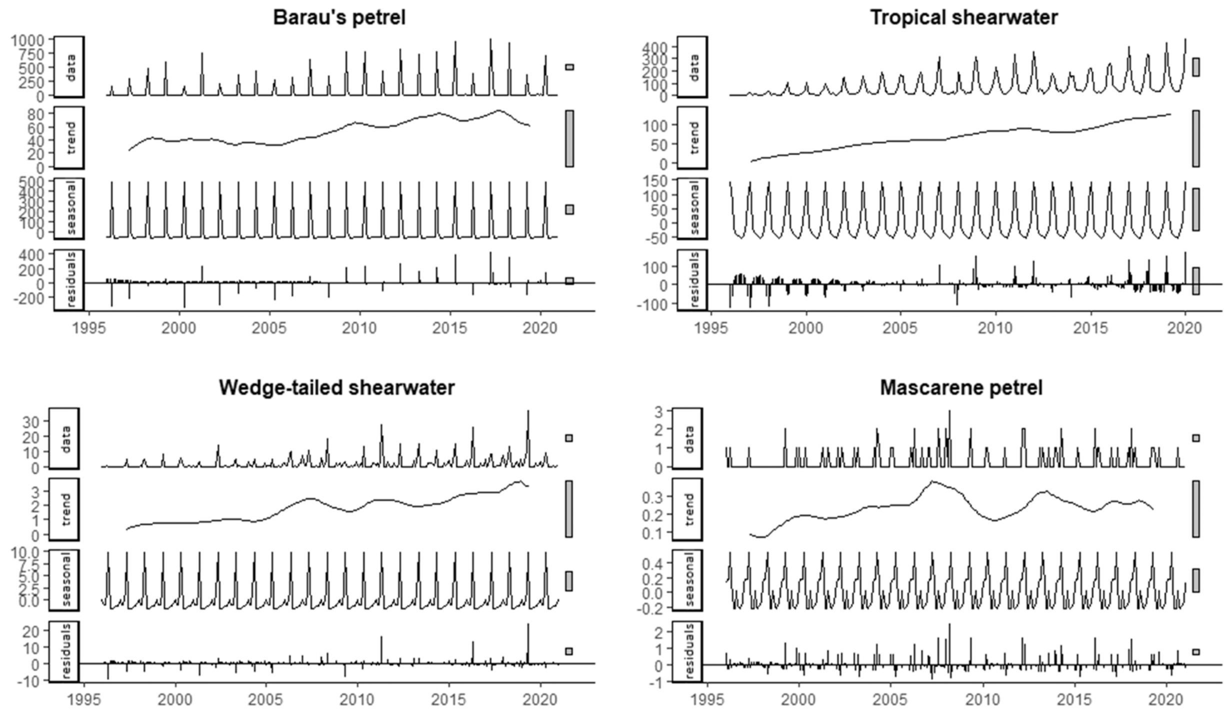

Fig. 4. Time series components of petrel groundings on Reunion Island from 1996 to 2020.

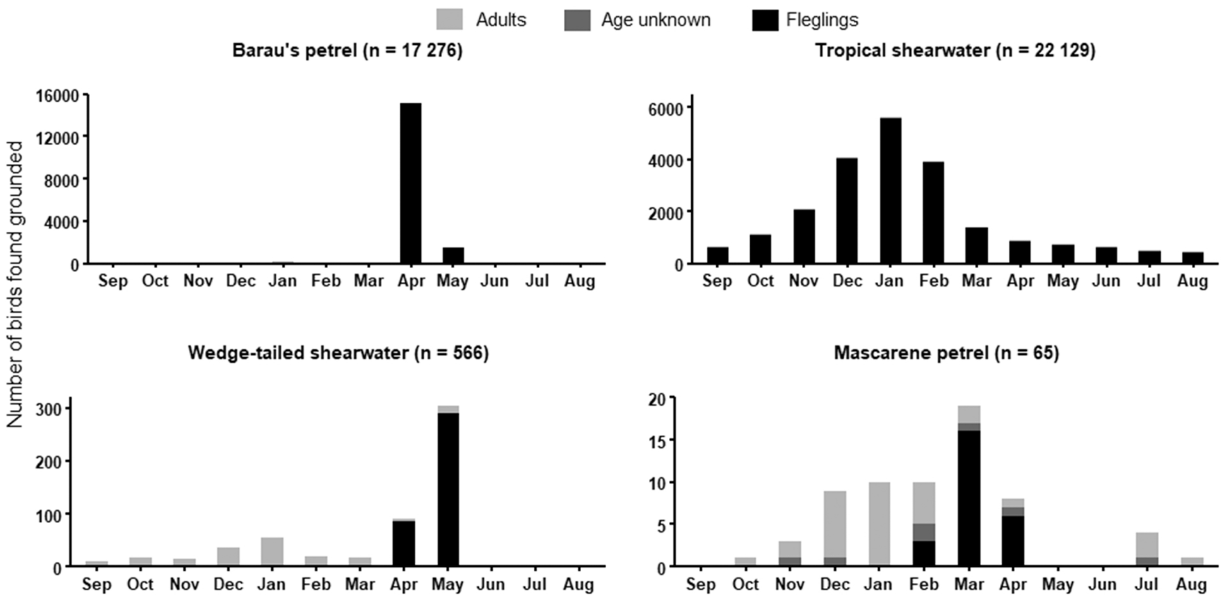

Fig. 5. Distribution of groundings by month from January 1996 to December 2021.

lesser extent, around May (May 15 ± 30 days).

3.4.4. Influence of the moon phase at fledging peak

Barau's petrel and wedge-tailed shearwater time series annual highest residuals are significantly correlated with the illuminated fraction of the moon at their respective fledging peaks (mean peak date of fledglings groundings): $\tau = -0.44$, p = .0021 for Barau's petrel and $\tau = -0.43$, p = .027 for wedge-tailed shearwater (See Appendix F). Years with a new moon close to the fledging peak have highly positive residuals (an excess of groundings compared to other years), while those with a full moon close to the fledging peak have substantial negative residuals (fewer groundings than expected). Time series residuals of Mascarene petrel and tropical shearwater are not significantly correlated with that factor, even when separated by region for the latter: $\tau = 0.051$, $p = .75$ for Mascarene petrel and $\tau = -0.18$, $p = .35$ for tropical shearwater (south region only, which is the region with the strongest correlation).

3.5. 2021–2050 projections

Models explaining annual petrel groundings include light pollution as a predictor for all species, as this variable is significantly correlated with all time series trends (See 3.4.2.). They also include the moon phase at fledging peak for Barau's petrel and wedge-tailed shearwater, as this variable shows a significant correlation with time series residuals for these two species (See 3.4.4.). Models explain a very large proportion of the variance of the data for Barau's petrel, tropical shearwater and wedge-tailed shearwater (respectively 83.4 %, 79.8 % and 89.5 %). Due to the low number of data for Mascarene petrel, its model explains 15.8 % of the variance.

Using the projections of light pollution (See Appendix G) and of the illuminated fraction of the moon at Barau's fledging peaks from 2021 to 2050, the models explaining each species' groundings were applied to predict the number of groundings of each species during this period. In total, around 60,000–87,000 petrels are expected to be found grounded from 2021 to 2050 on Reunion Island according to the different light pollution projections, i.e. around 2000–3000 each year on average (Table 1).

4. Discussion

4.1. Global analysis

4.1.1. Differences in number of birds found between species

The number of birds found grounded from 1996 to 2021 is very different according to the species: Barau's petrels and tropical shearwaters were found in very large numbers (respectively 17,276 and 22,129), while only 566 wedge-tailed shearwaters and 65 Mascarene petrels were found. This is due to differences in population sizes: Barau's petrel and tropical shearwater are estimated to be over 10,000 breeding pairs on Reunion island, against a few thousand for the wedge-tailed shearwater and only around 100 for the Mascarene petrel (Faulquier et al., 2017; Virion et al., 2021). Wedge-tailed shearwater might also be less affected by light attraction because most of its colonies are located on coastal cliffs (Faulquier et al., 2017), which considerably reduces their exposure to artificial lights compared to other species whose colonies are far inland (Gineste, 2016; Virion et al., 2021).

4.1.2. Temporal trends in the number of groundings between 1996 and 2021

The significant increase of the number of petrels found grounded on the island since 1996 (Fig. 1) is due to a combination of several factors. Light pollution, which has almost doubled during this period (See Appendix G), very probably played a major role in this increase. However, as the rescue campaign only relies on birds reported by the population, this increase might also have been caused by the growing awareness of the population as information campaigns were being implemented in the first decade, which increased the proportion of grounded birds reported to the SEOR. A part of the increase may also be caused by a growth of the breeding populations, but such increase has not been observed and is quite unlikely as all four species are facing multiple threats (Faulquier et al., 2017; Gineste et al., 2017; Virion et al., 2021).

4.1.3. Mortality rate

Depending on the species, 81.0–89.5 % of birds found grounded were released successfully, which means that thanks to the rescue campaign the mortality rate of grounded petrels is only 10.5–19 %. However, this rate might be greatly underestimated as an unknown fraction of grounded birds are not found and thus not rescued (Ainley et al., 2001; Rodríguez et al., 2014). Moreover, birds discovered dead tend to be underreported (Podolsky et al., 1998; Rodríguez et al., 2017b), and released birds may have a lower survival rate than

Table 1
Predicted number of petrel groundings on Reunion Island from 2022 to 2050, according to 3 light pollution projections.

Species	Predicted number of grounded birds	Light pollution projection		
		Business as usual	Regulation	Reduction
Barau's petrel	2022–2050 total	31,792	27,700	22,240
	Annual mean	1096	955	767
Tropical shearwater	2022–2050 total	53,265	46,362	37,485
	Annual mean	1837	1599	1293
Wedge-tailed shearwater	2022–2050 total	1532	1165	799
	Annual mean	53	40	28
Mascarene petrel	2022–2050 total	141	113	85
	Annual mean	5	4	3
All species	**2022–2050 total**	**86,730**	**75,340**	**60,609**
	Annual mean	**2991**	**2598**	**2090**

naturally fledged birds (Weimerskirch et al., 2019; Raine et al., 2020).

The rescue campaign still remains an important contribution to the conservation of affected species, as some of the rescued birds survive and subsequently reproduce: for example, as of 2021, 8 Barau's petrels and one Mascarene petrel banded as grounded fledglings have been found as breeding adults in surveyed colonies several years after their rescue (Authors' unpublished data). These numbers may seem very low compared to the amount of grounded fledglings rescued, but surveyed colonies only account for a very small proportion of all colonies, most of which are too difficult to access.

4.1.4. Proportion of fledglings among grounded birds

Barau's petrel, Tropical shearwater and wedge-tailed shearwater found grounded were mostly fledglings, which matches what is documented in the literature (reviewed in Rodríguez et al., 2017b). As for the Mascarene Petrel, adults are found grounded in greater numbers than fledglings, which is quite unusual among Procellariiformes. Data for this species are very low due to its rarity, so this proportion does not necessarily mean that adults are as attracted to light as fledglings. However, if confirmed, such light sensitivity of adults would be of particular concern for this critically endangered species, as an additive mortality on adults has a much greater demographic impact than on fledlgings (Virion et al., 2021).

4.2. Groundings characteristics

4.2.1. Spatial distribution

The spatial distribution of groundings (Figs. 2 and 3) show that most birds are found grounded in heavily light-polluted littoral cities, but also in mildly light-polluted areas near colonies. For example, despite being way less light polluted than big coastal cities, the town of Cilaos gathers a very large number of Barau's petrel groundings, because all colonies of this species are located in the mountains right above. Some birds also seem to have been found grounded in unlit areas (Fig. 3c): these places are actually isolated dwellings which have some lights, but in too small amount to be detected by satellite sensors. Despite producing very little light pollution compared to big coastal cities, these isolated dwellings still cause groundings because of their proximity to breeding colonies from where the young petrels fledge.

These results are consistent with other studies, which have shown that petrel fledglings are particularly attracted by lights visible from colonies (Rodríguez et al., 2015b), but also by those located along their flyways to reach the ocean (Troy et al., 2011, 2013). In addition, they may also be attracted back by lights visible from the ocean (Podolsky et al., 1998; Troy et al., 2013).

The distribution of Mascarene petrel groundings (appearing in yellow in Figs. 2 and 3c) is worth a note: most birds have been reported in the south of the island, where its known colonies are located (Virion et al., 2021), and those found on the western coast were probably attracted back after having successfully reached the ocean from these colonies. However, some birds have been found in the town of Salazie in the northeast of the island, which indicate that unknown colonies could be located in this region.

A major note must be made regarding the spatial distribution of groundings: as the rescue campaign relies exclusively on birds reported by general public, the island is not thoroughly surveyed following a standardized search effort. Even though grounded birds are reported all over the island, even in very scarcely populated places such as isolated dwellings in Cilaos (Fig. 3c), the probability for a grounded bird to be encountered may vary accordingly to population density. Thus, birds grounded in large coastal cities may tend to be reported more often than those falling in less densely populated areas. This highlights the limits of analyzing and interpreting data obtained from general public reports, and reminds that these results must be interpreted with great caution.

4.2.2. Moon phase influence on groundings intensity

As previously found in other studies (Reviewed in Rodríguez et al., 2017b), the number of grounded birds significantly decreases as the moon gets illuminated for all four species. This might be due to the fact that chicks would tend to fledge mostly during new moons and would avoid fledging during full moons, but radar surveys conducted near Barau's petrel colonies during the fledging period showed that chicks fledge throughout the period with no decrease during full moon (Gineste, 2016). This shows that full moons actually reduce the attraction of birds by artificial lights.

4.3. Proportion of fledglings affected and population estimates

4.3.1. Proportion of Barau's petrel fledglings affected by light pollution

The estimated minimal proportion of Barau's petrel fledglings affected by groundings is surprisingly low (3.93 %) regarding the very high numbers of birds found grounded. This estimate is based on the proportion of chicks banded before fledging that are subsequently found grounded (see Eq. 1 in 2.4.), so it is very likely to be underestimated, as an unknown proportion of grounded fledglings are found and reported. Furthermore, as observed by Rodríguez et al. (2022), some banded birds might be unnoticed some people involved in the rescue campaign are not professionals. Moreover, banded chicks may actually have a smaller risk of grounding than most others. Indeed, chicks occupying shallow, more accessible burrows are more likely to be banded. As such burrows are potentially more exposed to daylight, banded chicks may fledge with more developed visual systems, reducing their risk of stranding (Atchoi et al., 2020). As a consequence, the proportion of banded fledglings recovered grounded may be significantly smaller than that of other fledglings.

Nevertheless, our estimate still shows that if no action is undertaken to rescue grounded birds, more than 3.93 % of Barau's petrel fledglings produced each year would die because of light pollution. The proportion of Barau's petrel fledglings affected by groundings was previously estimated to be 20–40 % (Le Corre et al., 2002). The huge difference with our estimate mostly comes from the fact that a very different method was used to estimate the proportion in 2002, and the population size was underestimated at this time.

Similar studies conducted on different petrel species on other islands revealed very different estimated proportions of fledglings affected. In Balearic islands and Phillip Island, Australia, it is estimated that less than 1 % of fledglings are grounded by light pollution each year (Rodríguez et al., 2014, 2015a). In other places, this proportion is estimated to be significantly larger: 14 % in Tenerife (Rodríguez et al., 2015b), 15 % in Kaua'i, Hawai'i (Ainley et al., 2001) and around 15–20 % in Azores (Fontaine et al., 2011; Rodrigues et al., 2012). These different proportions may reflect disparities in light pollution levels on these islands, in location and light pollution exposure of colonies, or in light sensibility of affected species. However, the methods used are not the same in all studies and are often fairly unreliable (Rodríguez et al., 2017b), which makes any comparison difficult.

4.3.2. Barau's petrel population estimates

Barau's petrel breeding pairs were previously estimated between 10,000 and 30,000 with a mean estimate of 14,000 (Virion et al., 2021), though extremely large flows of birds observed by radar during the breeding period suggested that this number was underestimated (Gineste, 2016). Our estimate of 18 235–47,823 breeding pairs, with a mean estimate of 33,029, confirms that the breeding population of Barau's petrel is slightly larger than previously known. Interestingly, our study shows how groundings data can be used to estimate population size.

However, this estimate must be taken with great caution as it is very sensitive to the number of banded fledglings recovered grounded each year, which may be underestimated or unrepresentative of the rest of the population as explained in 4.3.1. To minimize bias, we thus excluded from our calculations years when no or too few banded fledglings were recovered. Moreover, this estimate is made with a very small proportion of fledglings banded on colonies, which limits its reliability. To allow more band recoveries among grounded birds and thus make this method more reliable, more fledglings need to be banded on different breeding colonies, including those in less accessible, deeper burrows. However, considering that breeding colonies are very remote and that the banding campaign must be carried out over a short period of time right before the young fledge, it is unlikely that the number of banded fledglings could be tremendously increased in the future.

4.4. Temporal analyses

4.4.1. Explanation of the trend by light pollution

For all species, the trend component of groundings time series is significantly correlated with light pollution. This suggests that the increase of artificial lights on the island is the main cause of the increase of groundings, even if other factors such as general public awareness could also have played a role as previously discussed in 4.1.2.

However, the interpretation of light pollution data retrieved from satellite instruments must be done with caution. VIIRS imagery acquires data late at night after most human nocturnal activity has already occurred, and thus many associated light sources have been turned off. This means that the light pollution levels used in this analysis are well below those that petrels actually perceive, because birds usually fledge during the first two hours after sunset (Gineste, 2016). Furthermore, VIIRS sensor cannot detect blue light, which are particularly emitted by white LED sources (Levin et al., 2020). This may lead to an underestimation of light pollution in recent years, during which white LEDs may have replaced older traditional sources.

4.4.2. Seasonality analysis

The seasonality and synchronicity of groundings of the four species are consistent with their breeding phenology (Pinet et al., 2009; Faulquier et al., 2017; Virion et al., 2021). Interestingly we found regional differences in fledging seasonality of tropical shearwaters, especially with birds of the southern part of the island fledging one month later than the birds of the northern and western parts of the island, suggesting that colonies do not have the same phenology throughout the island. To date, no tropical shearwater colonies have been studied on the island because all known colonies are virtually unreachable, and such regional differences were not documented so far. This shows how grounding data can be used to learn about the ecology of these poorly known species.

4.4.3. Influence of the moon phase at fledging peak

Both Barau's petrels and Wedge-tailed shearwaters have a very synchronized breeding regime, all fledglings leaving nests within a very short period of time (less than one lunar cycle). Any given year, when their peaks of fledging occur at full moon, the number of grounded birds is significantly lower than expected. This explains the strong correlation between the residual component of their time series and the moon phase. The two other species (tropical shearwater and Mascarene petrel) have a much more protracted breeding season, with fledgings occurring over several months and thus several lunar cycles. Because of this, the correlation of their time series residuals with the moon phase is not significant.

4.5. 2021–2050 projections

4.5.1. Models

Models built for Barau's petrel, tropical shearwater and wedge-tailed shearwater explain quite well the annual numbers of groundings. This shows how groundings are extremely linked to the factors used as explanatory variables in these models, i.e. light pollution for all species, and moon phase at fledging peak for Barau's petrel and wedge-tailed shearwater. However, a proportion of the variance of the data remains unexplained, due to the influence of other factors on annual grounding numbers, such as weather and variation in the number of fledglings produced. As these two factors cannot be reliably predicted, we choose not to include them in our models which are built for predictions. Thus, the predictions of the numbers of groundings expected in the future provided by our models will likely differ from actual numbers due to the influence of these other factors.

The model built for Mascarene petrel is weak, explaining only 15.8 % of the variance of the data. Annual numbers of groundings are extremely low for this species in comparison to others, thus these data are unfortunately insufficient to build a more reliable model.

4.5.2. Projected trends

Our projections from 2021 to 2050 (Table 1) give an overview of the number of petrels that may be impacted by light pollution in the coming decades on Reunion Island. These projections are made on the assumption that the petrel populations will remain stable. Groundings are intrinsically linked to human activity through light pollution, and thus will necessarily increase in the future if no significant actions are taken to reduce light pollution. Petrel populations are currently not suspected to be declining because of light pollution on Reunion island, thanks to the rescue campaign that reduces light-induced mortality (Gineste et al., 2017). However, this may change in the future if light pollution keeps increasing. Such a prospect would be all the more worrying as two of the affected species, Barau's petrel and Mascarene petrel, are endemic to the island and are already endangered and critically endangered respectively (Virion et al., 2021).

According to our projections and in the absence of a decline in petrel populations, groundings would decrease only if there is a strong reduction of light pollution (i.e. our "reduction" scenario). This might seem unlikely regarding the ongoing urban and economic development of the island, but many solutions exist to decrease light pollution without causing major inconvenience. Switching off all lights which are of little or no use is the most effective way to drastically reduce light pollution, but the impact of remaining lights can also be reduced with simple methods such as redirecting light to areas that need to be illuminated only, placing caches above them to prevent upward radiation, placing timers or motion sensors, or choosing warmer, less attractive wavelengths (Reed et al., 1985; Salamolard et al., 2007; Rodríguez et al., 2017a). Preventing the implementation of new lights despite ongoing urban and industrial development would also be necessary, although new lights might still be placed if they comply with the measures described above to limit their impact.

Various studies have shown that petrel fledglings are particularly attracted by lights visible from colonies (Rodríguez et al., 2015b), but also by those located along their flyways to reach the ocean (Troy et al., 2011, 2013). In addition, they may also be attracted back by lights visible from the ocean (Podolsky et al., 1998; Troy et al., 2013). Spatial distribution of groundings shows that all four petrel species breeding on Reunion island are affected not only by lights near colonies but also by illuminated areas many kilometers away (Fig. 3). Thus, measures to reduce light pollution must be implemented on the entire island to significantly reduce groundings. This would need significant awareness raising amongst lighting managers such as municipalities and sports ground managers, but also amongst the population.

4.5.3. Predictions reliability

Light pollution and moon phases are not the only factors inducing variations in the intensity of groundings: the annual number of groundings varies as well according to the number of fledglings produced annually, and to transient weather conditions such as fog, high winds or rain during fledging periods. As these factors cannot be reliably predicted at the scale of a year, unexpected variations in the annual number of groundings may occur compared to our long-term predictions.

4.5.4. Using groundings as a demographic indicator

Our projections are made on the assumption that petrel populations will remain stable. Thus, a drop in numbers of groundings without any reduction of light pollution would indicate that populations are declining (see for instance Rodríguez et al., 2011; Raine et al., 2017). Thereby, grounding numbers could be used in the future to remotely witness demographic trends or events and assess the impact of threats other than light pollution. In particular, such monitoring could help to identify a long term drop in fledgling numbers, due for instance to invasive predators at breeding colonies (rats and cats).

4.5.5. Importance of the rescue campaign

From January 1996 to December 2021, the rescue campaign carried out by the SEOR prevented the death of more than 35,000 birds. Maintaining the rescue campaign is essential for the conservation of all four petrel species on Reunion island. It remains the most effective way to reduce light-induced mortality, as our predictions suggest that up to 87,000 birds may be found grounded between 2022 and 2050.

5. Conclusions

To our knowledge, this study is the first to combine a retrospective analysis of 25 years of groundings with a predictive modeling of groundings for the next 30 years, comparing different scenarios of changes in light pollution. This study is also innovative through the use of time series analysis to separate long term trends, seasonal variations and short term variations of petrel groundings. It shows how this phenomenon is intrinsically linked with human impact through light pollution, but is also impacted by natural factors such as moon phases. It underlines as well how grounding data can be used to learn about affected species. We show that future prospects are worrying, as groundings are not predicted to decrease if light pollution is not significantly reduced. Up to around 90,000 petrels are predicted to be found grounded from 2021 to 2050 on Reunion island if no action is taken, underlining the dramatic need to maintain and strengthen the rescue campaign and implement drastic light reduction measures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2022.e02232.

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