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Biological Conservation 105 (2002) 93–102

BIOLOGICAL CONSERVATION

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Light-induced mortality of petrels: a 4-year study from Réunion Island (Indian Ocean)

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Received 8 December 2000; received in revised form 2 July 2001; accepted 30 August 2001

Abstract

We report the results of a study of light-induced mortality of petrels at Réunion Island which holds two endemic endangered species, Barau's petrel (*Pterodroma baraui*) and Mascarene petrel (*Pseudobulweria aterrima*), together with an endemic non threatened subspecies of Audubon's shearwater (*Puffinus lherminieri bailloni*). We collected 2348 birds attracted to lights between January 1996 and December 1999, among which 70% were Barau's petrels and 29% were Audubon's shearwaters. We found also three specimens of the very rare Mascarene petrel. Most grounded birds were fledglings (94%). Light-induced mortality was seasonal and linked with the breeding schedule of each species. At least 20–40% of the fledglings of Barau's petrels produced annually are attracted by lights. Light-induced mortality is a recent perturbation at Réunion Island. Thus, the effects of this disturbance on the population dynamics of these long lived seabirds may be hard to detect at the present time, but they are likely to occur in the near future. Conservation actions are proposed to limit the light-induced mortality together with other actions and long-term studies focused on the most endangered species.

Keywords: Seabird; Anthropogenic perturbation; Pterodroma; Pseudobulweria

1. Introduction

Because of their nocturnal habits at breeding places, petrels and shearwaters (Family Procellariidae, hereafter referred to as 'petrels') are known to be very sensitive to artificial lights (Imber, 1975). Fledglings are attracted by lights during their first flight to the sea, and many fall to ground with fatal injuries, are killed by predators or die of starvation. The main reason invoked to explain this attraction is that these species 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). The Family Procellariidae comprises about 80 species, among which 54% are endemic to one or a few islands (data from del Hoyo et al., 1992). Most endemic species have been recognised as threatened or endangered as a consequence of predator introduction to oceanic islands and of habitat destruction (Collar et al., 1994). Tropical and subtropical islands are of major conservation concern, as most endemic species (38 out of 44) are tropical or subtropical. As many of these tropical islands are inhabited by people, most endemic petrels may be potentially endangered by light-induced mortality. However very few studies focused on this threat.

In Hawaii, urban lights lead to extensive seasonal mortality of petrels (Telfer et al., 1987; Ainley et al., 1997). In this archipelago, this problem was identified very early (Hadley, 1961), and conservation efforts have been conducted each year since 1978 to reduce the impact of urban lights and other artificial structures on petrels (Reed et al., 1985; Telfer et al., 1987; Podolsky et al., 1998).

Réunion Island is the only oceanic island where two endemic species of petrels are known to breed, the Barau's petrel (*Pterodroma baraui*), and the very rare Mascarene petrel (*Pseudobulweria aterrima*). Both are

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0006-3207/02/$ - see front matter
PII: S0006-3207(01)00207-5

classified as Critically Endangered (Collar et al., 1994), as they suffer from poaching, predation at breeding colonies, and habitat destruction (Probst et al., 2000; Le Corre and Safford, 2001). A third species, the Audubon's shearwater (*Puffinus lherminieri*), is a pantropical species represented locally by a non-threatened endemic subspecies, *Puffinus lherminieri bailloni*. Although occasional light-induced mortality has been reported for all species of petrels breeding at Réunion Island since the early 1960s (Jouanin and Gill, 1967; Jouanin, 1987), no attempt was made to quantify this threat until 1996. From January 1996 to December 1999, public awareness campaigns were conducted to estimate the importance of light-induced mortality of fledgling petrels over the whole island, and to rescue grounded birds (Le Corre et al., 1996, 1999).

The aim of this paper is to describe the pattern of light-induced mortality of petrels at Réunion Island. Our data on species, geographic distribution and light types involved are also used to propose locally adapted actions to limit light-induced mortality of fledgling petrels.

2. Study area

Réunion Island (21°S, 55°E) is a mountainous volcanic island in the western Indian Ocean. Most urban and industrial areas are concentrated in the littoral region of the northern, western, and eastern slopes, whereas the southern slope and the inland regions are occupied by agriculture, forests, cliffs, and high rocky and lava areas (the highest point, Piton des Neiges at 3069 m.a.s.l.). Urbanisation and industrial infrastructures have increased considerably during the last 50 years and now occupies 6.7% of the total surface of the island, mainly at <500 m.a.s.l. (Raunet, 1991). Barau's petrel (4000 to 6500 pairs, Le Corre and Safford, 2001) breeds colonially in upland elfin forest of the centre of the island, above 2400 m.a.s.l. (Bretagnolle and Attié, 1991; Probst et al., 2000; Le Corre and Safford, 2001). Audubon's shearwater (3000–5000 pairs, Bretagnolle et al., 2000) also breeds mainly inland, between 50 and 1500 m.a.s.l., and some colonies are located on coastal cliffs (Gerdil, 1998; Bretagnolle et al., 2000; and personal observation). The breeding areas of the Mascarene petrel (<250 pairs, Attié et al., 1997), although suspected to be inland, are still unknown. Finally wedge-tailed shearwater (*Puffinus pacificus*) breeds in small colonies located mainly on coastal cliffs of the southern slope of the island, although some inland colonies are known. Thus, most birds (adults commuting between the sea and the colonies, and fledglings leaving the island) of all species except the wedge-tailed shearwater necessarily fly over urban areas before reaching the sea and are at risk of being attracted by lights.

3. Methods

3.1. Collection of the grounded birds

From January 1996 to December 1999, campaigns using local news media asked people to take dead and living fallen birds to their home and telephone the Natural History Museum of Réunion Island. The birds were collected daily by biologists of the Société d'Etudes Ornithologiques de la Réunion (Natural History Museum), examined, identified, and measured. Non-injured birds were ringed and released at the coast during daylight to avoid being attracted again by lights. Injured birds were held for rehabilitation or euthanised if fatally injured. Dead birds were kept frozen for further biological studies.

For each bird (dead or alive) we noted the place, date, moon phase and the occurrence and types of lights present at the place where the bird was found (years 1998 and 1999 only). To simplify the questionnaire to the people who found the birds, only broad categories of urban lights were defined: street lights and parking places, stadium and other lit sport structures (e.g. swimming pools), harbour and airports, individual houses, factories. Analysis of the geographic distribution of the light-induced mortality was based on 26 districts of the island (Fig. 1). For most birds found, we determined the age class (adults or fledglings) using feather colouration and wear, biometrics, presence of down or of an incubation patch. Moon phase was taken as a binary variable with periods of full moon (the exact day of full moon ± 1 day) and new moon and intermediate phases (all other days).

3.2. Impact of light-induced mortality on the population of Barau's petrel

Analysis of the impact of light-induced mortality was restricted to the population of Barau's petrel only because this species bears the heaviest mortality each year (Section 4). To estimate the impact of light-induced mortality we needed to assess the total number of fledglings lost (FL) and the total number of fledglings produced annually by the population (FP). We assumed that all birds found grounded would have died if they had not been taken by people. Fallen birds do not fly but seek a dark hiding place where they would have succumbed to hypothermia, starvation, predation or accidents with vehicles.

The proportion of fledgling lost (proportion lost, PL) is then

$$PL(\%) = FL/FP \times 100 \quad (1)$$

The total number of FL annually through attraction to lights is very hard to estimate and depends on the

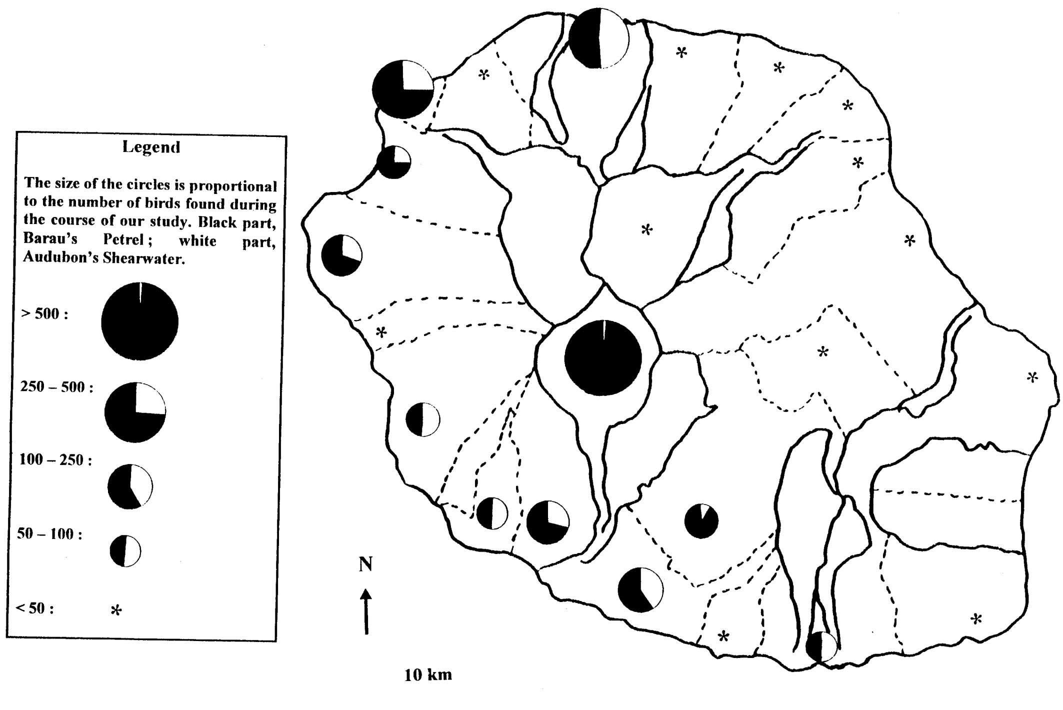

Fig. 1. Geographic distribution and importance of light-induced mortality of Barau's petrel and Audubon's shearwaters at Réunion Island.

efficiency of the information campaigns conducted each year before the fledging seasons. The number of birds found increased each year from 1996 to 1999 (Section 4) as a consequence of the campaigns. For the present purpose, we assumed that in 1999 most grounded birds were found by people and notified to us. Thus we used the number of birds found in 1999 to estimate PL in Eq. (1).

The number of fledglings produced annually depends on the fledging success (FS, number of birds which successfully fledge out of the number of eggs laid per females), on the adult population size (N in pairs) and on the proportion of breeders in the adult population (BP). Therefore the number of fledglings produced each year is:

$$\mathrm{FP} = N \times \mathrm{FS} \times \mathrm{BP} \quad (2)$$

then

$$\mathrm{PL}(\%) = \mathrm{FL}/(N \times \mathrm{FS} \times \mathrm{BP}) \quad (3)$$

These parameters are difficult to assess on islands like Réunion and, apart from population size, they have never been estimated for Barau's petrels. For the purpose of our study we used published figures (Simons, 1984) of fledging success (FS = 0.66, the average breeding success without significant predation at colonies) and proportion of breeders in an adult population (BP = 89%) available for the Hawaiian dark-rumped petrel (*Pterodroma sandwichensis*), a closely related tropical gadfly petrel, similar in size to Barau's petrel (Imber, 1985; Bretagnolle and Attié, 1991).

4. Results

4.1. Present pattern of the light-induced mortality on petrels

4.1.1. Species account, age related variation and success of the rescue campaigns

From January 1996 to December 1999, we found 2348 fallen petrels in urban areas. Barau's petrels and Audubon's shearwaters represented 99% of the birds (1643 and 674 or 70% and 29%, respectively). Three live Mascarene petrels were found; two were released but the third died of starvation. Twenty-eight wedge-tailed shearwaters were also found, although this Indo-Pacific species is uncommon in Réunion island. The mean number of birds found annually was 587±301, but there was a constant increase in the number of birds found, this progression being the consequence of an increasing awareness of the human population (Table 1). In 1999, we found 900 petrels: 604 Barau's petrels (596 fledglings and eight adults), 283 Audubon's shearwaters (258 fledglings, six adults and 19 of unknown age), 12 wedge-tailed shearwaters (11 fledglings and one adult) and one Mascarene petrel (a fledgling).

Most birds (94% when considering the four species) were fledglings, probably leaving their nest for the first time when attracted by lights (Table 2). Less than 10%

Table 1
Number of petrels and shearwaters found stranded at Réunion Island from January 1996 to December 1999

	1996	1997	1998	1999	Total	Frequency (%)
Barau's petrel (*Pterodroma baraui*)	160	359	520	604	1643	70.0
Mascarene's petrel (*Pseudobulweria aterrima*)	0	1	1	1	3	0.1
Audubon's shearwater (*Puffinus lherminieiri bailloni*)	53	122	216	283	674	28.7
Wedge-tailed shearwater (*Puffinus pacificus*)	1	6	9	12	28	1.2
Total	214	488	746	900	2348	

Table 2
Age of the birds found and success of the rescue campaigns

Species (sample size)	Age classes			
	Adults	Fledglings	Age unknown	Successfully released (%)
Barau's petrel (1643)	1.1%	98.9%	0	90.0
Mascarene's black petrel (3)	1	1	1	66.6
Audubon's Shearwater (674)	3.4%	82.2%	14.4%	92.1
Wedge-tailed shearwater (28)	2	26	0	92.9
Total (2348)	1.9%	94.0%	4.2%	90.6

of the birds were found dead or dying, or unable to fly again, and euthanised. Thus rescue campaigns released more than 90% of the birds (Table 2).

4.1.2. Seasonal aspects and effects of moon phases

Light-induced mortality occurred during every month of the year, but clear seasonal patterns linked with the breeding phenology of each species were apparent (Fig. 2). Audubon's shearwaters were the least seasonal species with birds found all the year round, but 72% of the birds (96% fledglings) were found between November and February. This corresponds to a laying period between July and October. Barau's petrels breed synchronously during the austral summer, with most fledglings leaving the colonies in April and May (Jouanin and Gill, 1967; Jouanin, 1987). Most Barau's petrel mortality occurred in April (92%) and May (6%), and all birds found in this period were fledglings. Some adults were found in February, March, and September. The wedge-tailed shearwater is also a summer breeder in Réunion (Jouanin, 1987) and all fledglings were found in April (27%) and May (73%). The three Mascarene petrels were found in summer as well (an adult in November 1997, a bird of indeterminate age in February 1998 and a fledgling in March 1999).

Significantly fewer Barau's petrels and Audubon's shearwaters were found daily during full moon than at other stages of the lunar cycles (Table 3). For Barau's petrels, the effect of full moon was particularly clear in 1997 when this coincided with the normal fledging peak (Fig. 3).

4.1.3. Geographic distribution of light-induced mortality

The distribution of the birds found was related to the distribution of the urban and industrial areas and to the distribution of the breeding colonies of each species (Fig. 1). For all species, most birds were found in the lower parts of the northern and western slopes of the island, where urban lights are most abundant. However, 35% of the Barau's petrels were found at Cirque de Cilaos (1500 m.a.s.l.), in the centre of the island (Fig. 1). This small town (6000 inhabitants in 1999), the highest town of the island, is located just below the main breeding colonies of Barau's petrels. Few Audubon's and wedge-tailed shearwaters were found at Cilaos (4 and 1%, respectively) because colonies of these species are few and small at this altitude.

Considering all species together, 61% of the birds were found in four towns: Cilaos (25%), Saint Denis (15%), Le Port (11%) and Saint Pierre (10%). A further 12% were found in the urbanised belt of the leeward coast (Saint Paul, Saint Gilles, La Saline).

4.1.4. Light-induced mortality in relation to light types. The type of light involved was known for 1102 birds out of the 2348 recorded. This concerned Barau's petrels (777) and Audubon's shearwaters (325). Street lights were the main type recorded (61%) followed by sport installations (17%) and harbour infrastructures (11%). The other types of lights (airport, individual houses, factories) represented $<5\%$ of the mortality each. There were differences in the types of lights involved in petrel mortality between the five main districts concerned by this threat. At Saint Denis, Saint Pierre and the built up belt between Saint Paul and La Saline, most mortality cases (77–84%) occurred at places lit by street lights. At Cilaos, the main problem occurred at the two floodlit sports facilities of the town (51%) whereas street lights accounted for 48% of the cases censused. At Le Port, the main mortality was due to the harbour lighting

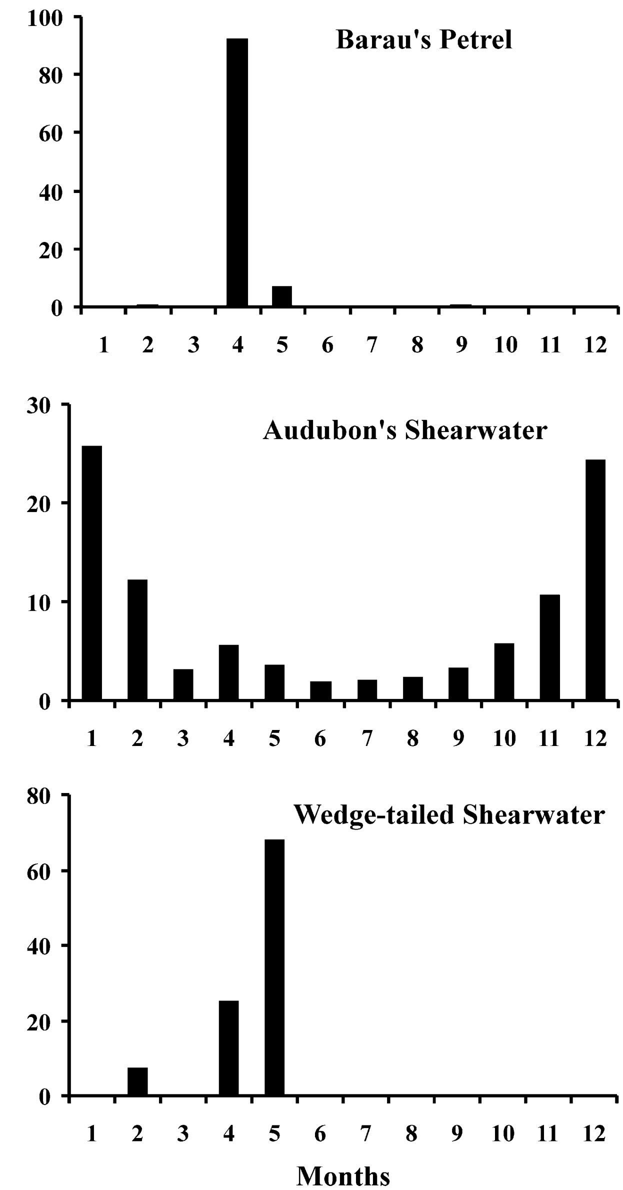

Fig. 2. Annual distribution of the light-induced mortality of Barau's petrel, Audubon's shearwater and Wedge-tailed shearwater (1996–1999). 1 is for January, 12 for December.

infrastructures (72%) and to a lesser extent to street lights (22%).

4.2. Estimation of the light-induced mortality at the population level

We used Eq. 3 (Section 3) and the data obtained in 1999 on fledgling Barau's petrels (NR = 596 fledglings found grounded) to estimate the importance of the light-induced mortality at the population level. Assuming a breeding success of 66% and that 89% of the adults breed annually (Simons, 1984), we estimated that 20% of the fledglings produced annually are lost through attraction to lights.

5. Discussion

5.1. Characteristics of the light-induced mortality of petrels at Réunion Island and comparison with other places

A great variety of petrel species are attracted by lights (see Imber, 1975 for a review and Table 4), but this phenomenon has been studied in detail only in Hawaii (Reed et al., 1985; Telfer et al., 1987; Ainley et al., 1997; Podolsky et al., 1998). Although the species involved are different, there are similarities between these studies and our findings. In both places the phenomenon was seasonal and related to the breeding schedules of each species. It affected primarily fledglings during massive "fallout" periods. Our 4-year study showed that light-induced mortality was important for Barau's petrels (70%) but the four breeding species were attracted by lights, including the very rare and critically endangered Mascarene petrel. In Hawaii three species were concerned (Table 4), but only one, the threatened Newell's shearwater (*Puffinus auricularis newelli*), underwent massive fallout (up to 1800 birds found per year, Telfer et al., 1987). In both cases, this threat affects threatened and endangered endemic species or subspecies, and may accelerate the decline of these species.

At Réunion Island a great diversity of artificial lights attracted birds, and the more numerous and widespread types of lights (streetlights and sport installations) were responsible for most cases of mortality (78%). The geographic distribution of the mortality depended on location of urban and industrial areas in relation to the distribution of breeding colonies. The mortality occurred mainly in the coastal towns of the western and northern slopes (Saint Denis, Le Port, Saint Pierre, Saint Paul), but 36% of the Barau's petrels were found in the single upland town of Cilaos, located just beyond the main colonies of Barau's petrels. A similar pattern linked with both urbanisation and colony location was found in Kauai island (Telfer et al., 1987).

Very few Barau's petrels and Audubon's shearwaters were found grounded during full moon compared with new moon or intermediate moon phases. An identical effect of the moon was found on Kauai during the fledging period of Newell's shearwaters (Reed et al., 1985; Telfer et al., 1987). The decrease in number of birds attracted by lights during full moon may indicate that full moon inhibits young petrels from fledging or that fledglings are not attracted by lights because a greater ambient light causes a diminution of attraction of artificial lights (Reed et al., 1985).

Discriminating between these two hypotheses has important conservation implications because in the latter hypothesis, birds flying away during full moon would avoid light-induced mortality, whereas in the former all birds would be potentially attracted by artificial lights. If the latter hypothesis were true, fewer birds would be attracted by lights in years when full moon occurred in the middle of the fledging peak (e.g. 1997), compared with years when the full moon was at the beginning (1998) or at the end (1999) of the normal fledging period. There were indeed fewer birds found in 1997 compared with 1998 and 1999, but this was also true when considering the number of Audubon's shearwaters found during the full year, suggesting that these differences were due to an increasing awareness of the human population rather than an effect of moon phase. Furthermore, the daily schedules of the fledging suggest that in some years young petrels were forced not to fly until ambient light decreases. For example, in 1997, fledging apparently ceased during full moon and lasted longer than in the other years, indicating that birds stayed longer in the burrows. During that year, fledglings found during the last part of the fledging period tended to be lighter and to have a longer wing than in the other years, suggesting that they did remain longer in their burrows (Jullian and Payet, 1999). In 1998, fledging was apparently delayed and started massively a few days after the full moon, again suggesting that the birds stayed in the burrows until light conditions were favourable.

These observations suggest that full moon inhibits the activity of fledgling petrels at colonies. This is consistent with the fact that adults petrels are less active at colonies during full moon in numerous places including Réunion Island (e.g. Imber, 1975; Bretagnolle et al., 2000; and personal observation). From a conservation viewpoint, this indicates that all fledglings are potentially endangered by artificial lights, whatever the date of the full moon.

Table 3
Mean number of birds found daily during fledging peaks of Barau's petrels (April 1996–1999) and Audubon's shearwaters (January, February and December 1998 and 1999) in relation with the moon phases

	Full moon	Intermediate moon phases	Mann–Whitney *U* test
a: Barau's petrels			
1996	0.0±0.0 (3)	6.1±6.9 (26)	*
1997	0.3±0.6 (3)	10.9±11.6 (27)	*
1998	0.0±0.0 (3)	17.6±21.5 (27)	*
1999	1.0±1.4 (4)	22.5±25.5 (27)	*
Total	0.4±0.9 (13)	14.3±18.8 (106)	**
b: Audubon's shearwaters			
1998	0.5±0.7 (9)	1.5±1.7 (81)	*
1999[a]	0.8±1.0 (9)	2.6±2.3 (74)	**
Total	0.6±0.8 (18)	2.0±2.0 (155)	**

[a] There is only 83 days in 1999 because the rescue campaign stopped between 25/12 and 31/12.
* $P<0.05$.
** $P<0.01$.

5.2. Long-term effects on the populations

5.2.1. Barau's petrels

We estimated that 20% of the fledglings produced each year were attracted by lights. This estimate is based on the assumption that in 1999 we found all the grounded birds (596). This is probably false as numerous grounded birds may have been killed before being found. Furthermore some birds may have been found by poachers or by unaware persons and killed or let loose. Thus there are probably >20% of birds lost annually through light attraction.

We calculated an annual production of fledglings of 2940 per year, assuming a breeding population of 5000 pairs, a proportion of breeders of 89%, and a breeding success of 66%. The figure of 5000 pairs is probably close to reality as most colonies are known now (Probst et al., 2000; Probst, personal communication). This figure is a little higher than previous estimates of the population (Bretagnolle and Attié, 1991: at least 3500

Table 4
Regional survey[a] of the urban light-induced mortality of petrels worldwide, and of the occurrence of rescue campaigns

Places	Species	Importance	Rescue campaign	Authors
Madeira	*Bulweria bulwerii*, *Puffinus puffinus*, *Pterodroma madeira*, *Calonectris diomedea*	?	No	Zino, personal communication
Canaries	*C. diomedea*, *Puffinus assimilis*, *Puffinus puffinus*	+ + +	Yes	Martin, personal communication
Hispaniola	*Pterodroma hasitata*	?	?	Wingate, 1964 (in Imber, 1975)
Hawaii Is.	*P. phaeopygia*, *Puffinus auricularis newelli*, *O. castro*	+ + +	Yes	Telfer et al., 1987.
New Zealand	*Pterodroma macroptera*, *Procellaria parkinsoni*, *Puffinus huttoni*	+ +	Yes	Imber, 1975; Tully, personal communication
Gau I., Fiji	*Pseudobulweria macgillivrayi*	+ +	No	Watling, personal communication
Gough I.	*Pterodroma brevirostris*	?	?	Swales, 1965 (in Imber, 1975)
French Polynesia	Pseudobulweria rostrata	+	Yes	Raust, 1997
New Caledonia	*Pterodroma nigripenis*, *Pseudobulweria rostrata*	+	No	Ingrid, personal communication
Réunion	*Puffinus pacificus*, *Puffinus lherminieri bailloni*, *Pterodroma baraui*, *Pseudobulweria aterrima*	+ + +	Yes	This study

[a] This survey is based on available information on light-induced mortality. It is not an exhaustive one as this threat may happen at every place where petrels and human coexist).

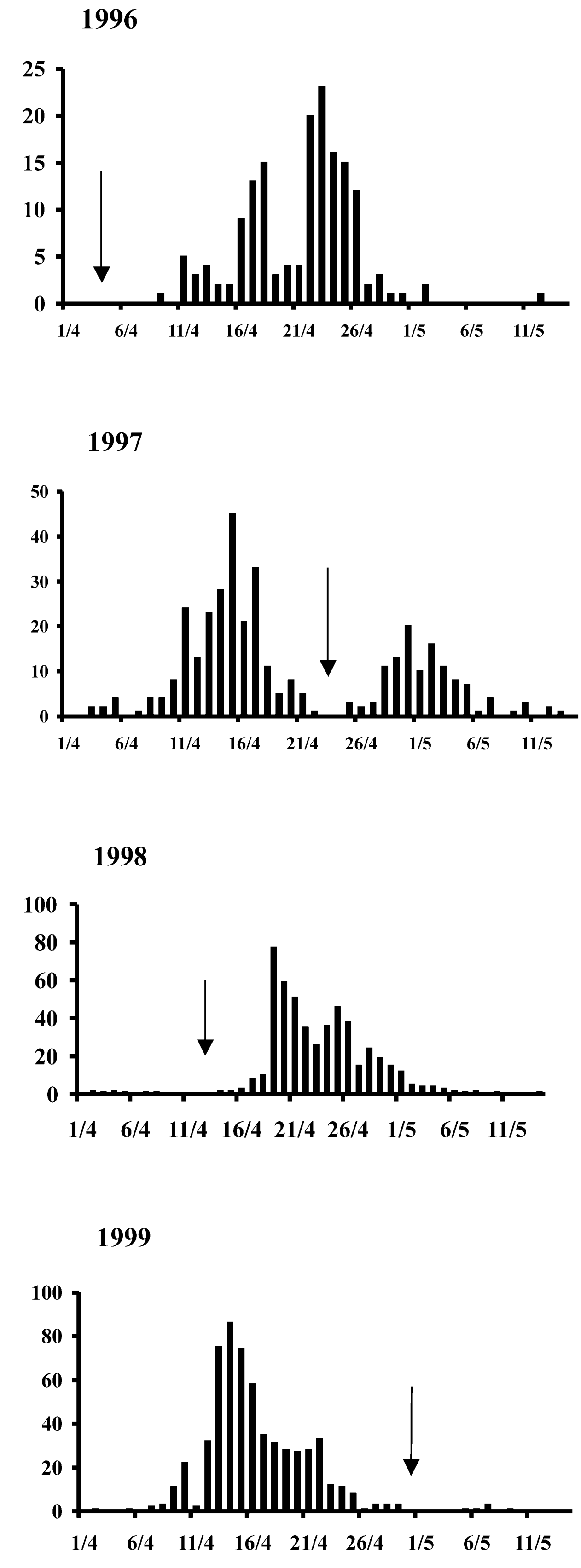

Fig. 3. Daily schedule of the fledging of Barau's petrels in relation with the moon phases (1996–1999). Arrows indicate the date of the full moon each year.

pairs; Stahl and Bartle, 1991: 2200–3800 pairs) but it takes into account the recent findings of several large colonies (Probst et al., 2000; Probst personal communication; Le Corre and Safford, 2001). The average breeding success of 66% is based on the work of Simons (1984), who found that without any significant predation, the average breeding success of the Hawaiian dark-rumped petrel is 66%. Barau's petrel is very closely related and similar in size and ecology to the dark-rumped petrel, thus it may have a comparable breeding success without any predation. However, recent field work at breeding colonies has shown that rats and cats are present at most colonies (Probst et al., 2000; Le Corre and Safford, 2001; Probst personal communication). Knowing the considerable impact of predators on the breeding success of medium sized petrels (e. g. Simons, 1985; Thibault, 1995), we can suppose that the breeding success of Barau's petrel is on average $<66\%$. If we assume a breeding success of 35% (breeding success when predators are present at dark-rumped petrel colonies, see Simons, 1984), then the annual fledging production drops down to 1557 and the calculation of the proportion of birds lost through light attraction gives 38%.

Given these two causes of underestimation (all the birds grounded are not found, and the annual fledgling production is probably less than expected because of predation at colonies), we assume that the proportion of fledgling Barau's petrels lost annually through light attraction is 40%.

Sincock (in Reed et al., 1985) estimated that in Kauai, 50% of the fledglings of Newell's shearwaters were lost through light attraction, but the long-term effect of this loss on the population is not known.

Simons (1984) has shown by a model of the population dynamics of the Hawaiian dark rumped petrels that if 8% of the fledglings produced annually were lost through light attraction, the population would decline at a rate of 1.5% per year. A loss of 20% would increase the rate of decline to 3% per year. Although the demographic parameters of Barau's petrel population are not known, we can suppose that the population cannot sustain an additive fledgling mortality of 20–40% per year. Thus this population is probably declining as a consequence of light-induced mortality.

5.2.2. Other species

Audubon's shearwaters breed in all suitable habitats throughout the island, in >200 small colonies and the population size is probably >3000–5000 pairs (Gerdil, 1998; Bretagnolle et al., 2000). We found "only" 258 fledglings grounded in 1999 suggesting that this species is less affected by lights than Barau's petrels. Considering an annual production of fledglings of around 1500–2500 fledglings (half of the pairs produce a fledgling) we can estimate that the proportion of fledglings attracted by light per year may be between 10 and 17%. Although this rate of loss is less than in the Barau's petrel, it may endanger the population of Audubon's shearwater as well (Simons, 1984).

We found three Mascarene petrels between 1996 and 1999. Only three other specimens were found during the whole twentieth century, in 1970, 1973 (Jouanin, 1987) and 1995 (Attié et al., 1997). Among the six birds found during the twentieth century, five were found in an urban area. This suggests that this species like all petrels is attracted by lights and that some birds may be killed each year by urban lights (see also Jouanin, 1987).

5.2.3. *When did the decline begin?*

According to our results, Barau's petrels (and Audubon's shearwaters to a lesser extent) may be declining as a consequence of additive mortality of fledglings due to light attraction. An important point is to know when this decline began. Nocturnal and burrow-nester seabirds are notoriously difficult to monitor and this difficulty is enhanced at Réunion Island because of the rough topography of most breeding places. Consequently we have no historical data on the population size of petrels at Réunion Island. Several studies have been conducted between 1964 and 1999 but they are heterogeneous and circumstantial and are inadequate for detecting all but drastic changes in the population (Gill, 1967; Bretagnolle and Attié, 1991; Stahl and Bartle, 1991; Probst et al., 2000; Le Corre and Safford, 2001; Le Corre et al., unpublished data; Probst, personal communication). These studies did not provide any evidence of important population decline between 1964 and 1999.

On the other hand, we have precise information on the growth of the human population size on the island and on the production of electricity during the last 60 years (Fig. 4), both parameters probably closely related to the density of artificial lights on the island. Although population growth was linear from 1940 to 2000, the production of electricity increased exponentially during the same period, suggesting that the present density of artificial lights on the island is very recent (<10 years, Fig. 4). For example there were only 46 lit floodlit sports facilities in 1970 in the whole island, compared with 97 in 1980, 245 in 1992 and a forecast of 400 in 2000 (Anon, 1993). As mortality is directly related to lights and not to the number of inhabitants on the island, we suggest that the present rate of light-induced mortality is very recent, and this factor probably began to be a major threat for petrel populations <10 years ago. This is consistent with the apparent stability of Barau's petrel population observed during the last 40 years.

Like all long-lived seabirds, tropical gadfly petrels like the Barau's petrel have delayed maturity (Simons, 1984) resulting in a time lag of ca. 6 years between the beginning of an artificial increase in fledgling mortality and its potential effects on recruitment of new adults to the breeding population. Thus, the reduced fledging success, although important for the long term dynamics of the population (see earlier) has small short-term effects on it.

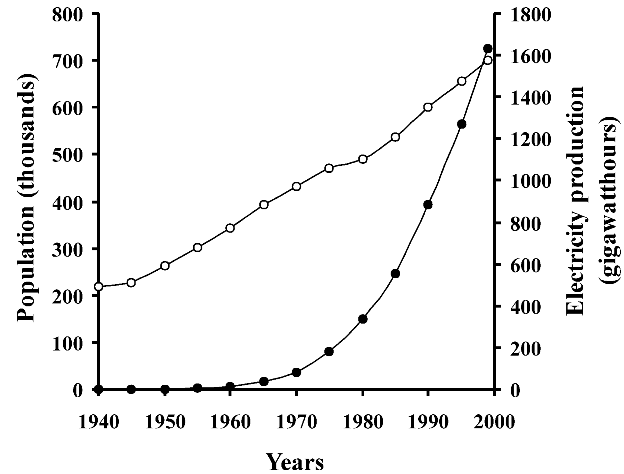

Fig. 4. Growth of the human population and of the production of electricity at Réunion Island during the last 60 years. Open circles, human population; closed circles, electricity production. Data on human population from Vaxellaire (1995), data on electricity production from Eletricité de France—Direction Régionale de La Réunion, (C. Vidot personal communication).

In conclusion, this perturbation is a very new one, which probably has just begun to induce a still barely perceptible decline of the population.

5.3. *Conservation plan*

At Réunion, several actions are planned or in progress to reduce the proportion of birds lost through light attraction.

5.3.1. *Shielding upward radiation and reducing artificial lights*

In Hawaii, Reed et al. (1985) have shown experimentally that light shielding decreases the attraction of Newell's shearwaters by nearly 40% and hence has management potential. This could be done at Réunion Island, particularly at the sites which attract most birds. Furthermore, we found that the mortality of Barau's petrels was very seasonal and foreseeable in relation with the moon phase and concentrated in some well defined places (floodlit sports facilities and streets of Cilaos, harbour of le Port, etc.). In addition to the shielding, a practical conservation measure could be to restrict the use of lights during the peak of fledging each year (April).

5.3.2. *Continuation of the rescue campaigns*

However, we can hardly imagine reducing significantly the use of artificial lights in a modern and densely populated island like Réunion. To our knowledge, rescue campaigns already exists at various islands including the Canaries, Hawaii, New Zealand, French Polynesia and Réunion (Table 4). Our 4-year experience has convinced us that rescue campaigns may be the best way to significantly reduce this cause of mortality. Ninety percent of the birds found were released successfully and the large media coverage greatly increased the chance of a grounded bird being found and released. As yet, we have no means of estimating the survival of these birds during the few days after being released, but as all rescued birds were ringed, then data should become available in the future.

5.3.3. Monitoring and long-term study of the species

There is a need to establish a monitoring method that will quantify any population change. Knowing the breeding behaviour of the species and the topography of the breeding ground, the best way may be to do simultaneous counts of the returning birds when they cross the beaches at dusk, as has been done since 1997 (unpublished data). Furthermore, the annual monitoring of the number of fledglings attracted by lights should give indirect estimates of the annual production of fledglings. However, our prediction of a decline of the population is made imprecise because of the lack of accurate data on the life history of this species. Furthermore, this imprecision is enhanced by a lack of knowledge on the impact of introduced mammals at colonies. Finally, we have no idea of what happens to the hundreds of fledglings rescued each year after their release: do they die as a consequence of the stress or internal injuries induced by their failed first departure or do they behave as other fledglings? Such a question may be answered by studying the recruitment of the new breeders at colonies. More generally, there is a need of a better knowledge of the species, and the next step will be to initiate a long term study of the species at colonies.

Acknowledgements

We are indebted to all volunteers who participated in the rescue campaigns: J. Bried, S. Brugerolle, B. Cain, M. Charrière, Y.-M. de Viviès, N. Gaidet, J.-P. Gauthier, T. Gerdil, T. Ghestemme, G. Jacubek, H. Joslain, J. Legentil, P. Lys, O. Marié, J.-P. Palencia, S. Payet, J.-M. Probst, M. Rochet, B. Rogez and Y. Tortrotau. We also thank the teachers and the pupils of the primary school of Mare Sèche (Cilaos), and the security staff of the harbour of Le Port for their invaluable help respectively at Cilaos and at Le Port. We gratefully acknowledge the veterinarians, policemen, firemen, the staff of the Natural History Museum and all the anonymous persons who kindly helped in rescuing the birds all over the island. The Office National des Forêts and the Conservatoire Botanique de Mascarin provided accommodations of biologist volunteers at Cilaos and Saint Leu. We also thank C. Vidot (EDF—Réunion) who kindly provided data on the production of electricity at Réunion. Fundings for this programme was provided by the French Ministry of the Environment (DIREN—Réunion), the FEDER (EC), Electricité de France (EDF—Réunion), Optique de Bourbon, Banque de La Réunion, Foucque S. A., GISOM (Groupement d'Intérêt Scientifique sur les Oiseaux marins, Muséum National d'Histoire Naturelle, France) and BirdLife International (LPO). We are grateful to J. Bried, F. Courchamps, M. Imber, S. Legendre, M. Salamolard, Brian Davis and to anonymous referees for their constructive comments on earlier drafts of the manuscript. Finally we thank C. Hazevoet, M. Imber, A. Martin, R. Tully, and F. Zino who kindly provided unpublished information on light-induced mortality of petrels at various places.

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