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The impact of introduced predators, light-induced mortality of fledglings and poaching on the dynamics of the Cory's shearwater (*Calonectris diomedea*) population from the Azores, northeastern subtropical Atlantic

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ABSTRACT

Cory's shearwater (*Calonectris diomedea*) is a procellariiform seabird which breeds in the Mediterranean and the north-eastern subtropical Atlantic, and which is considered "Vulnerable" in Europe due to recent declines at some localities. In the Azores archipelago (Atlantic), the introduction of mammalian predators by man has led to petrels being extirpated from the main islands, except for Cory's shearwater. Currently, the Azorean population of Cory's shearwaters represents 65% of the species' world population. However, its dynamics remains unknown, although: (1) numbers might have declined by 43% between 1996 and 2001, (2) on the main islands, the young suffer mortality from introduced mammals, poachers, and urban lights upon fledging, and (3) at sea, the level of fishery mortality remains unknown.

To fill this gap, we conducted a 7-year demographic survey on a mammal-free islet in the Azores to determine adult survival rate using capture-mark-recapture of the breeders and to estimate fecundity. We also assessed urban mortality using the data from the rescue campaigns annually conducted in the archipelago. Urban mortality concerned about 6% of fledglings, but its importance greatly varied among islands. When rescue campaigns occur, the rate might drop below 0.5%. Overall, our simulations concerning the next 100 years do not allow excluding a decrease in Cory's shearwater numbers in the Azores without rescue campaigns (by 87% under the least favourable scenario). Rescue campaigns should only slow down the decline unless, simultaneously, lower competition for nests compared to Vila islet allows adults to breed almost every year on the main islands and juvenile survival exceeds a threshold value. Since adult survival rate was high (>0.93), an eventual decline of the Azorean population of Cory's shearwaters would probably not result from fishery mortality of adults, but rather from poor fledgling productivity and perhaps also from low survival during the first year at sea.

1. Introduction

The Order Procellariiformes (i.e., albatrosses and petrels) holds the highest proportion of threatened species among all seabird taxonomic orders (49% of 129 species; BirdLife International, 2010). Many procellariiform species breed on oceanic islands that were free of mammalian predators, until the latter were introduced by man. Therefore, most procellariiformes, and especially burrow-nesting petrels, lack the ecological, behavioural and life-history traits that would enable them to cope successfully with introduced predators (Warham, 1990), whose impact proved to be catastrophic in most cases (reviews in e.g., Courchamp et al. (2003), Blackburn et al. (2004)). Other threats on land are human disturbance, vandalism (Monteiro et al., 1996b), and urban light-induced mortality of fledglings upon departure to sea at night (Telfer et al., 1987; Le Corre et al., 2002; Rodríguez and Rodríguez, 2009). At sea, fishery-induced mortality resulting from entanglement in longline hooks or trawls has been shown to be responsible for the decline in the numbers of several species (review in e.g., Brooke (2004)).

Cory's shearwater (*Calonectris diomedea*) is a burrow-nesting petrel which breeds in the Mediterranean and in the north-eastern subtropical Atlantic (Thibault et al., 1997), and which overwinters in the southern hemisphere, essentially off Brazil and South Africa (González-Solís et al., 2007). Mediterranean populations have been suffering heavy fishery-induced mortality since the last decades (Belda and Sánchez, 2001; Cooper et al., 2003). In the Atlantic, thousands of birds were slaughtered by people on the Salvages islands, resulting in a decrease by more than 90% in the breeding numbers from this locality between 1970 and 1977. Even though

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the size of the Salvages population has resumed increasing since the end of massacres, current numbers still remain well below historical values (Mougin et al., 2000; Granadeiro et al., 2006). For these reasons, the species is considered "Vulnerable" in Europe (BirdLife International, 2004). On the Canary islands, light-induced mortality of fledglings is potentially high (Rodríguez and Rodríguez, 2009), but nothing is known about the population dynamics.

With an estimated population size of *ca* 188,000 breeding pairs, the Azores archipelago (Atlantic ocean) holds about 65% of the world population of Cory's shearwaters and 75% of the population of the *borealis* subspecies (BirdLife International, 2004). However, a census conducted in the whole archipelago in 2001 yielded a 43% lower estimate compared to the previous census in 1996, whose results correspond to the data published by BirdLife International (2004). Both censuses were conducted using the same methods and under similar conditions concerning weather and observers' experience (Bolton, 2001a). Since (1) colony attendance may show important inter-annual variations in petrels (Chastel et al., 1993; Jenouvrier et al., 2005), and (2) a different behaviour of the birds in 2001 might also explain the observed decline (Bolton, 2001a), it remains impossible to know whether lower numbers in 2001 reflect such phenomena (which are not related to mortality) or higher mortality. While the fishery mortality levels faced by Azorean Cory's shearwaters remain undetermined, the threats on land have been identified. First, introduced rats (*Rattus rattus* and *Rattus norvegicus*) and feral cats (*Felis catus*) consume eggs and chicks on the nine main islands of the archipelago. Second, illegal poaching of chicks for food regularly occurs on one island. Third, fledglings suffer urban light-induced mortality throughout the archipelago during their departure to sea at night (Monteiro et al., 1996b). The impact of light pollution on petrels has already been assessed at several localities (review in Le Corre et al. (2002), Rodríguez and Rodríguez (2009); Miles et al. (2010)). In the Azores, urban light-induced mortality has led to the implementation of rescue campaigns since 1995.

Despite the existence of these potentially important threats, the demographic parameters and the dynamics of the Azorean population of Cory's shearwaters remain totally unknown. The importance of the Azores as a breeding locality for the species makes it necessary to fill this gap. To do this, we conducted a 7-year demographic survey involving capture-mark-recapture of the breeders and chick ringing. We used our estimates of adult survival rate, breeding frequency and breeding success and accounted for mortality on land (due to introduced predators, poaching and artificial lights) to model the long-term dynamics of the Azorean population in order to assess its viability and determine the part played by potential threats.

2. Methods

2.1. Study area and species

The study was conducted in the Azores archipelago, which is made up by nine islands (total area: 2333 km^2) lying along a 600 km transect (36°55′–39°43′N, 25°–31°07′W; Fig. 1).

Cory's shearwaters attend colonies from late February to early November. Like in all procellariiform species, the female lays a single egg without replacement if incubation fails (Warham, 1990). Chicks hatch in late July and leave the colonies from late October to early November (Monteiro et al., 1996a,b).

The species breeds on the nine islands and the majority of the 26 islets of the archipelago, coexisting with introduced mammalian predators on all the islands (De León et al., 2005). Poaching of chicks occurs essentially on Santa Maria island, and thousands of fledglings are attracted by artificial lights each year.

2.2. Demographic survey

A demographic survey was conducted from 2002 to 2008 on Vila islet (8 ha), off Santa Maria island (Fig. 1). The islet holds around 400 breeding pairs of Cory's shearwaters and is free of introduced predators (Monteiro, 2000; this study). Our study plot holds *ca* 70 breeding pairs.

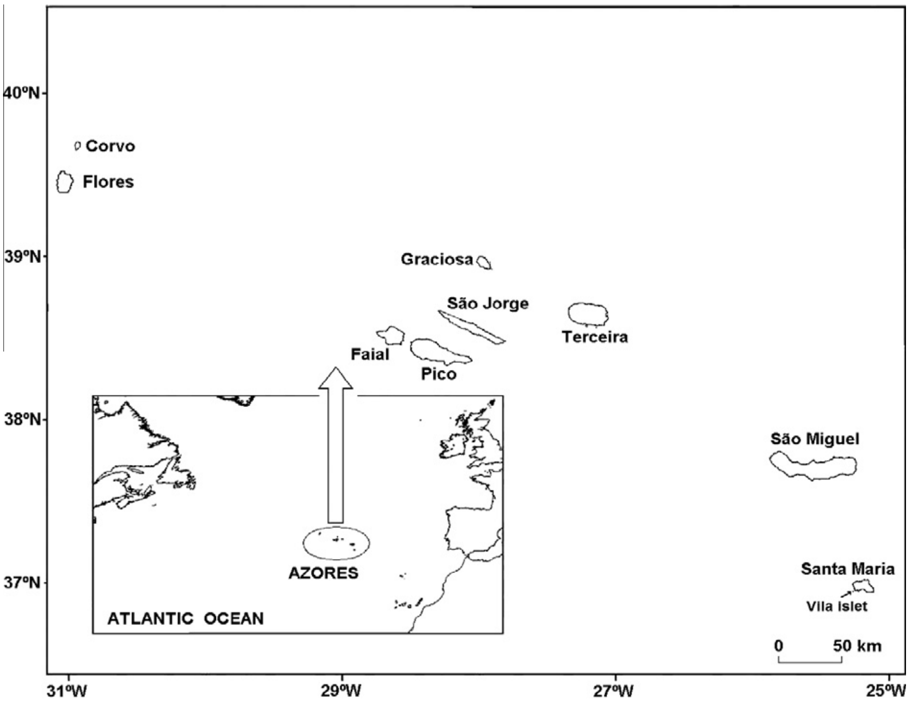

Fig. 1. Situation of the Azores archipelago.

Nests were checked during incubation and before fledging in order to determine breeding success, i.e. the proportion of eggs yielding a fledgling. Overall, we monitored 452 reproductive episodes and ringed 268 chicks.

During incubation, we also carried out a capture-mark-recapture monitoring on the breeders. In 2002, 128 breeding adults were initially captured in their burrows, and ringed or identified from their rings if already ringed. When recaptured during subsequent years, they were identified and their reproductive status upon recapture (breeder or non-breeder, depending on the presence/absence of an egg in the burrow) recorded. Each year, the adults that bred in our study colony for the first time were included in the study, and we also walked throughout our study plot at night to recapture (in their nests or on the open ground) former breeders that returned to the colony as non-breeders. Altogether, 268 adults (137 females and 131 males; for sexing methods see Bried et al., 2010) were monitored from 2002 to 2008. Although Cory's shearwaters are able to breed every year, some individuals can skip breeding years (Mougin et al., 1997; this study). Therefore, we determined the proportion of breeders (BP) during a given year in the adult population (see Le Corre et al., 2002). BP is the number of birds known to have made at least one breeding attempt in the past and breeding this year plus the number of first-time breeders this year, divided by the total number of birds known to have attempted to breed in the past and known to be alive this year plus the number of first-time breeders. When determining BP, we used only the birds whose breeding status was known during their entire capture-mark-recapture history. For instance, let us consider an individual which was observed with its usual partner during years 1, 3 and 4, with the breeding status of the pair being known each time, but which was not observed during year 2 whereas its usual partner bred without identified mate in the usual nest. Given that temporary divorces sometimes occur in Cory's shearwaters (Mougin et al., 1987b), including on Vila (this study), this bird was excluded from calculations.

Capture-mark-recapture modelling (e.g. Lebreton et al., 1992 for a review) allowed us to estimate adult survival probabilities using program E-SURGE (Choquet et al., 2009b). As our general model, we considered the Cormack–Jolly–Seber (CJS) model (Φ_{g*t}, p_{g*t}) with both survival (Φ) and recapture probabilities (p) being sex- (noted g) and time-dependent (noted t).

Using program U-CARE (Choquet et al., 2009a), which implements specific contingency table procedures, we assessed the fit of the general CJS model to determine whether it provided an adequate description of the data (review in Pradel et al., 2005). The general model fitted the data poorly ($\chi^2_{32} = 69.4$, $P = 0.0001$). A closer inspection revealed that the lack of fit was entirely explained by component 2.CT, which detects heterogeneity in recapture probability (males: $\chi^2_4 = 15.4$, $P = 0.004$; females: $\chi^2_4 = 40.3$, $P < 0.0001$). This indicated "trap happiness" (Pradel, 1993), meaning that capture probability at year $t + 1$ was higher for individuals captured at year t (average value: 0.811, SE = 0.040) than for individuals not captured at year t (average value: 0.426, SE = 0.071). Following Gimenez et al. (2003), we incorporated an effect of time elapsed since last recapture when modelling recapture probability. This effect distinguishes between the two events that a capture occurred or not during the previous occasion (Pradel, 1993). After accounting for trap-dependence (Pradel et al., 2005), the fit of the model was satisfactory ($\chi^2_{24} = 13.67$, $P = 0.95$).. Therefore, we tested all the models by including the trap-dependence effect (noted m). The most parsimonious model was identified using the second-order Akaike Information Criterion AICc. Two models were considered distinct when ΔAICc was higher than two (Burnham and Anderson, 2002).

2.3. Threats

2.3.1. Introduced predators

Predation by introduced mammals occurs on the nine main islands (Monteiro et al., 1996b). Although the Azorean population might be less severely impacted than Mediterranean populations (Thibault, 1995; Furness et al., 2000), we estimated breeding success with respect to the presence/absence of these predators. While our survey on Vila islet allowed determining breeding success in the absence of alien mammals, a previous study (Tamagnini Mendes, 2008) had determined breeding success in the presence of introduced predators at the colony of Morro de Castelo Branco on Faial island in 2006. We used the latter estimate when considering breeding success on the nine main islands.

2.3.2. Light-induced mortality

In the Azores, urban light attraction was identified in the early 1990s. Following the example of Hawaii (Reed et al., 1985), rescue campaigns have been carried out throughout the archipelago every year since 1995, from mid-October to mid-November.

Most of the birds found on Faial island during the rescue campaigns from 2001 to 2008 (note that 2004, for which no data are available, was not considered) were fledglings (99.8% of 3099 birds of known age, for a total of 3231 birds found). Consequently, we considered that adults are not affected by light attraction.

Following Le Corre et al. (2002), we defined the proportion of fledglings lost (i.e., light-induced mortality) as the number of fledglings lost (FL) divided by the total number of fledglings produced annually by the population (FP):

$$\mathrm{PL} = \mathrm{FL}/\mathrm{FP}$$

While FL comes from the data collected during the rescue campaigns, the number of fledglings produced every year is:

$$\mathrm{FP} = N \times \mathrm{BP} \times \mathrm{BS}$$

where N is the number of breeding pairs, BP the annual proportion of breeders in the adult population and BS the breeding success (BP and BS were obtained as explained in Section 2.2). Therefore

$$\mathrm{PL} = \mathrm{FL}/(N \times \mathrm{BP} \times \mathrm{BS})$$

Nevertheless, we assessed the light attraction effect and the consequences of rescue campaigns by calculating two mortality rates (instead of calculating only PL). First, the potential light-induced mortality (hereafter LIM), for which FL corresponds to the total number of birds found (alive and dead), is the light-induced mortality in the absence of rescue campaigns (we considered that without rescue campaigns, all the grounded birds would die; Le Corre et al., 2002; Rodríguez and Rodríguez, 2009). Second, the effective light-induced mortality ($\mathrm{LIM_{sos}}$) is the mortality despite the rescue campaigns, with FL being the number of birds found dead or that die before being released.

Since all grounded birds cannot be found, LIM and $\mathrm{LIM_{sos}}$ must be considered as minimum rates. However, the campaigns became more efficient over the years, and we based our calculations on the number of birds found during that of 2008 (when human effort to save the birds was highest) to obtain as realistic estimates as possible. Light-induced mortality was determined for each island and the entire archipelago.

2.3.3. Poaching

Field observations suggest that 500 to 1500 nestlings are taken annually on Santa Maria island (J. Bairos – Regional Environment Directorate from the Azores, unpubl. data). Knowing that poaching only concerns chicks, poaching-induced mortality (PIM) was calculated in the same manner as for light-induced mortality, that is:

$$\mathrm{PIM} = \mathrm{PC}/\mathrm{FP}$$

where PC is the number of poached chicks and FP the number of fledglings produced annually by the population (see Section 2.3.2 for details). Minimum ($\mathrm{PIM}_{\mathrm{min}}$) and maximum ($\mathrm{PIM}_{\mathrm{max}}$) poaching mortality corresponded to 500 and 1500 nestlings collected every year, respectively.

2.4. Modelling population dynamics

Population trends over time were determined by matrix modelling (Caswell, 2001). Simulations were run by using a pre-breeding matrix with the software ULM (Legendre and Clobert, 1995; Ferrière et al., 1996). We structured the life cycle of the population by age and breeding status based on its life-history traits (Caswell, 2001; Lebreton, 2005; see Appendix A). Since the duration of our demographic survey did not allow determining age at first reproduction on Vila islet, we used data from the Salvages islands where Cory's shearwaters start breeding between 4 and 13 years, the average being 8.9 years (Mougin et al., 2000). Therefore, we considered that until 2 years old, birds are immature. From 3 years, they were considered as pre-breeders (PB) with the possibility to start breeding the next year. The PB class contains birds between 3 and 12 years old. Pre-breeders can become breeders (B) with the probability $\Phi_{PB} \times P_{i\to B}$ or remain pre-breeders with the probability $\Phi_{PB} \times (1 - P_{i\to B})$, where Φ_{PB} is the pre-breeder survival and $P_{i\to B}$ the probability for a *i* years old bird that has never yet bred to breed the next year. Since all birds are breeders at 13 years old, $P_{12\to B}$ is equal to 1. The different values of $P_{i\to B}$ (see Appendix B) were calculated using the data presented in Table 1 of Mougin et al. (2000), and considering only the cohorts for which recruitment into the breeding population was completed during the study of these authors (cohorts from 1977 to 1986 included).

A breeder can breed again the next year with the probability $\Phi_a \times P_{B\to B}$ (Φ_a being the adult survival rate), or take a sabbatical year ($\Phi_a \times (1 - P_{B\to B})$). Once non-breeder, a bird can resume breeding ($\Phi_a \times (1 - P_{NB\to NB})$) or skip another breeding year ($\Phi_a \times P_{NB\to NB}$). Yearling females are produced with the probability $\alpha \times BS \times \Phi_j$ where α is the sex-ratio, BS the breeding success and Φ_j the juvenile survival. $P_{B\to B}$ ($P_{NB\to NB}$) represents the average proportion of breeders (non-breeders) in year *n* that survived and bred (did not breed) the year $n + 1$. Breeding probabilities concerning former breeders were calculated from our 7-year demographic survey (Appendix B), and considering only the cases where the breeding status of our study birds was known (which represent 96% of cases, including the birds that were not recaptured during a given year but survived). Due to the impact of introduced mammals, however, breeding densities (and hence, the level of competition for nests) may be lower on the colonies situated on the main islands than on Vila islet. We accounted for this by re-doing the simulations considering an extreme situation, that is, $P_{B\to B} = 0.9$ (G. Hémery and J.-C. Thibault, unpubl. data), which was the value observed on the Lavezzi islands, Corsica, before rat eradication (at this time, competition for nests was much weaker than on Vila islet), and which is also close to the estimate obtained on the Chafarinas islands where introduced rats are present as well (0.89; Igual et al., 2009). Indeed, the probability for Cory's shearwaters to skip breeding years increases if the size of the breeding population (in other words, if the level of competition for nests) increases (Mougin et al., 1987a).

Table 1
Range of the sensitivities of the demographic parameters of Cory's shearwaters in the Azores, after accounting for variations in juvenile survival ($\Phi_j = 0.4$, 0.5 or 0.6) and for light-induced and poaching mortality.

	Vila (LIM = 0, PIM = 0)	Azores (LIM > 0, PIM > 0)
Adult survival Φ_a	0.634–0.699	0.649–0.719
Pre-breeder survival Φ_{PB}	0.234–0.285	0.217–0.276
Immature survival Φ_i	0.082–0.101	0.076–0.098
Juvenile survival Φ_j	0.079–0.096	0.074–0.093
Fecundity f[a]	0.131–0.161	0.128–0.165

[a] When considering the whole archipelago, the impact of introduced predators on breeding success was taken into account, and we set $P_{B\to B}$ to 0.781.

Since young birds come back for breeding after several years at sea, the duration of our study could not allow estimating survival rates for other age classes than adults, i.e., juveniles, immatures and pre-breeders. On the Lavezzi islands, Mediterranean, the survival rate of Cory's shearwaters during their first year at sea is 0.52 (Jenouvrier et al., 2008). However, it may have reached 0.6 during the recovery phase of the population on the Salvages islands (Mougin et al., 1990), although it was probably much lower (0.288) when this population was prosperous and competition for food stronger (Mougin et al., 1987a). Therefore, we conducted our simulations using three arbitrarily chosen values for juvenile survival: 0.4, 0.5 and 0.6. We considered that immature and pre-breeder survivals were equal to adult survival since mortality of young Cory's shearwaters at sea mainly occurs during the first months after fledging (Mougin et al., 1987a).

Population modelling was conducted in two steps. First, deterministic simulations with constant demographic parameters allowed determining the population growth rate λ as the dominant eigenvalue of the matrix. Then, we ran a stochastic model using Monte-Carlo simulations in order to estimate extinction probabilities, that is, the proportion of trajectories leading to population extinction among the total number of trajectories (in each case, we ran 1000 trajectories with ULM). The temporal variability of breeding success and breeding probability was considered to follow a beta distribution, with mean and standard deviation being those of each of these two parameters. Simulations were performed using a time horizon of 100 years.

Simulations were conducted for the populations of Vila islet, each of the nine islands and the whole archipelago. When considering the latter, we neglected the population breeding on mammal-free islets in our analyses given that it represents less than 2% of the entire Azorean population (L.R. Monteiro, R.S. Feio, V.C. Neves and authors' unpubl. data).

3. Results

3.1. Demographic parameters

From 2002 to 2008 on Vila islet, breeding success averaged 0.586 (SD = 0.118), and the proportion of breeders in the adult population (BP) was 0.765.

According to capture-mark-recapture modelling, sex effect was not retained, either on survival probabilities or on recapture probabilities. The best model was the model [$\Phi(t)$, $p(m + t)$], with both survival and recapture probabilities time-dependent (model [$\Phi(t)$, $p(m + g + t)$] including a sex effect on recapture rates had ΔAICc < 2 but more parameters, Appendix C). Mean adult annual survival on Vila islet was estimated at 0.934 (SE = 0.013; range: 0.906–0.973).

3.2. Threats

Urban mortality was observed from mid-October to mid-November. Considering that (1) breeding success on the main islands is 0.556 (Tamagnini Mendes, 2008) and (2) the proportion of breeders in the adult population is 0.765%, 6.5% to 6.6% of fledglings (after accounting for poaching, see below and Appendix D) are victim of urban lights each year throughout the archipelago (5167 birds were found grounded in 2008). Faial and Pico were the islands with the highest mortality rates (19.7% and 15.2% of fledglings, respectively). Rescue campaigns greatly helped to diminish urban mortality since 92.7% of the individuals found in the archipelago in 2008 were successfully released (Appendix D). Therefore, overall mortality dropped to less than 0.5%, reaching 1.2% in the worst case (on Pico island; Appendix D; Appendix E).

On Santa Maria island, annual poaching mortality rate ranged from 0.096 ($\mathrm{PIM_{min}}$) to 0.288 ($\mathrm{PIM_{max}}$). On the Azores scale, this represented a decrease in fledgling numbers comprised between 0.6% ($\mathrm{PIM_{min}}$) and 1.9% ($\mathrm{PIM_{max}}$).

3.3. Sensitivity analyses

Although sensitivities slightly differed between models, population growth rate was mainly affected by variations in adult survival. The other demographic parameters had low sensitivities (Table 1).

3.4. Modelling population dynamics

3.4.1. Vila islet

The annual growth rates generated from deterministic modelling ranged from 0.987 when Φ_j was set to 0.4, to 1.005 when Φ_j was set to 0.6. Numbers remained stable for $\Phi_j = 0.545$ (Fig. 2).

Monte-Carlo simulations revealed that none of the stochastic trajectories led to extinction during the next 100 years. Breeding numbers would drop to 109 pairs if $\Phi_j = 0.4$ and reach 627 pairs if $\Phi_j = 0.6$. Expected extinction time was 496 years for $\Phi_j = 0.4$ and 1713 years for $\Phi_j = 0.5$.

3.4.2. Main islands

In the absence of light- and poaching-induced mortality and when $P_{B\to B}$ was set to 0.781, deterministic modelling predicted population growth rates of 0.985 and 1.002 when Φ_j was set to 0.4 and 0.6, respectively. A juvenile survival of 0.574 (0.481 when $P_{B\to B}$ was set to 0.9) was required to have a stable population (Fig. 2, Appendix D). Trends were similar when considering urban mortality when rescue campaigns are conducted ($\mathrm{LIM_{sos}}$), although population growth rates (λ) slightly decreased. The most important decrease concerned Pico where λ fell by 0.05% when Φ_j was set to 0.4 and 0.5. At the Azores scale, λ declined by 0.02% regardless of juvenile survival. When considering light-induced mortality without rescue campaigns (LIM), numbers should decline even if $\Phi_j = 0.6$ (Appendix D). Predicted decline ranged from 0.24% (for $\Phi_j = 0.4$) to 0.30% (for $\Phi_j = 0.6$) at the Azores scale, reaching 0.96% on Faial when juvenile survival was set to 0.6. Regardless of the value given to $P_{B\to B}$, light-induced mortality affected λ (LIM vs LIM = 0 or $\mathrm{LIM_{sos}}$, Φ_j and poaching mortality being equal) *ca* three times more, in terms of both absolute and relative decrease, than did poaching mortality ($\mathrm{PIM_{max}}$ vs PIM = 0, Φ_j and light-induced mortality being equal), that is, λ decreased by 0.21–0.30% instead of decreasing by 0.07–0.09% (Appendix D).

On Santa Maria island, numbers would decrease at a maximum rate (i.e., with $\Phi_j = 0.4$, LIM) of 1.6% per year in the absence of poaching. When also accounting for poaching, the maximum decrease rate reached 2.8% per year (Appendix D). Since annual decrease rates did not exceed 2.3% (value predicted for Faial) on the other islands, the population from Santa Maria had the lowest potential growth rate within the archipelago.

Table 2
Values of breeding success allowing the Cory's shearwater population from the Azores to remain stable under the different scenarios of light-induced and poaching mortality. Before slash: $P_{B\to B} = 0.781$; after slash: $P_{B\to B} = 0.9$.

Juvenile survival	LIM, $\mathrm{PIM_{min}}$	LIM, $\mathrm{PIM_{max}}$	$\mathrm{LIM_{sos}}$, $\mathrm{PIM_{min}}$	$\mathrm{LIM_{sos}}$, $\mathrm{PIM_{max}}$
$\Phi_j = 0.4$	0.859/0.711	0.870/0.719	0.807/0.675	0.817/0.682
$\Phi_j = 0.5$	0.687/0.569	0.696/0.575	0.646/0.540	0.654/0.546
$\Phi_j = 0.6$	0.573/0.474	0.580/0.479	0.538/0.450	0.545/0.455

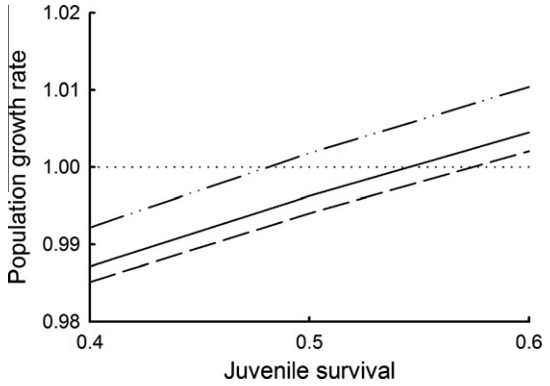

Fig. 2. Effect of juvenile survival on the annual growth rate of the Cory's shearwater population from the Azores, with respect to the presence (on the nine main islands, LIM = PIM = 0) or the absence (on Vila islet) of introduced predators. Upper line: Azores, $P_{B\to B} = 0.9$; middle line: Vila islet ($P_{B\to B} = 0.781$); bottom line: Azores, $P_{B\to B} = 0.781$.

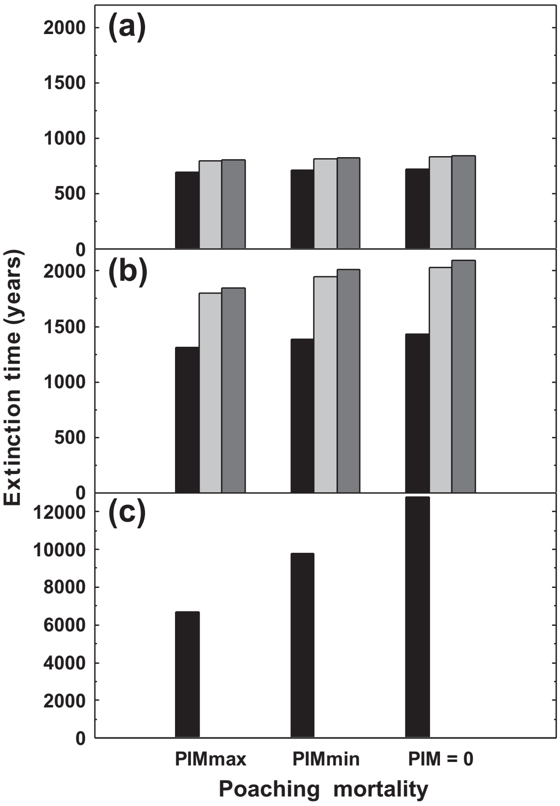

Fig. 3. Results from stochastic modelling showing the effect on light-induced and poaching mortality on extinction times. Black bars: LIM; pale grey bars: $\mathrm{LIM_{sos}}$; dark grey bars: LIM = 0. (a): $\Phi_j = 0.4$, (b): $\Phi_j = 0.5$, (c): $\Phi_j = 0.6$. $P_{B\to B}$ was set to 0.781.

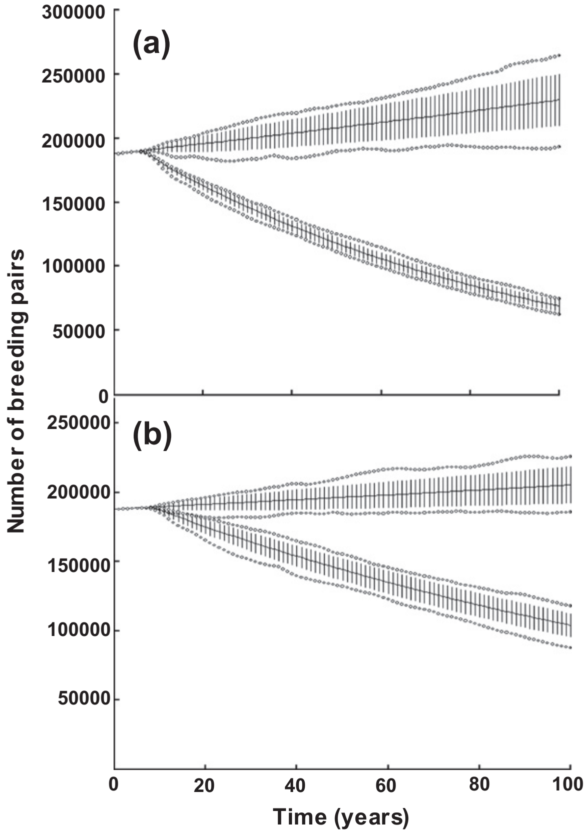

Fig. 4. Simulated stochastic trends of the Azorean population of Cory's shearwaters with 2-SD confidence intervals (bars) and maximum and minimum values (open circles). (a) Top curve: $\Phi_j = 0.6$, no urban and poaching mortality, $P_{B\rightarrow B} = 0.781$; bottom curve: $\Phi_j = 0.4$, LIM and PIM_{max}, $P_{B\rightarrow B} = 0.9$. (b) Top curve: $\Phi_j = 0.5$, LIM_{sos} and PIM_{max}, $P_{B\rightarrow B} = 0.9$; bottom curve: $\Phi_j = 0.5$, LIM_{sos} and PIM_{min}, $P_{B\rightarrow B} = 0.781$.

Monte-Carlo simulations did not predict any extinction of the Azorean population over the next 100 years. Under the least favourable scenario ($P_{B\rightarrow B} = 0.781$, LIM, PIM_{max} and $\Phi_j = 0.4$), expected extinction time was 689 years (Appendix G). To ensure population stability if $P_{B\rightarrow B} = 0.781$ and in the absence of rescue campaigns, juvenile survival should reach 0.618 (0.511 when $P_{B\rightarrow B}$ was set to 0.9) with poaching-induced mortality = PIM_{min}, or 0.626 (0.517 when $P_{B\rightarrow B} = 0.9$) with poaching-induced mortality = PIM_{max} or, alternatively, annual breeding success should vary from 0.573 to 0.870 (0.474–0.719 when $P_{B\rightarrow B} = 0.9$), depending on the value of Φ_j (Table 2).

If rescue campaigns occur and $\Phi_j = 0.5$, numbers should decrease if $P_{B\rightarrow B} = 0.781$ and should increase if $P_{B\rightarrow B} = 0.9$, regardless of poaching mortality (Fig 3; Appendix G). Φ_j should reach 0.581 (0.485 when $P_{B\rightarrow B} = 0.9$) with PIM_{min} or 0.588 (0.491 when $P_{B\rightarrow B} = 0.9$) with PIM_{max} to have a stable population. Alternatively, annual breeding success should vary from 0.538 to 0.817 (0.450–0.682 when $P_{B\rightarrow B} = 0.9$), depending on the value of Φ_j (Table 2).

Our stochastic simulations also showed that light-induced mortality should affect extinction times and population size at $t + 100$ years much more strongly than should poaching mortality (Fig. 3; Appendix G). When considering all the 27 simulations and an initial population size of 188,000 pairs, stochastic modelling using $P_{B\rightarrow B} = 0.781$ led to 230,100 breeding pairs in the best case ($\Phi_j = 0.6$, no poaching, no urban mortality) and 30,380 breeding pairs (that is, a decrease by 87%) in the worst case ($\Phi_j = 0.4$, PIM_{max}, LIM) at $t + 100$ years. In the latter situation, numbers should decrease even if $P_{B\rightarrow B} = 0.9$ (Fig. 4; Appendix G).

4. Discussion

In our simulations, exchanges with other localities were not considered, that is, we considered that the number of immigrants equalled that of emigrants. Likewise, we considered that no additional environmental (earthquakes regularly occur in the Azores and are sometimes violent) or anthropogenic changes susceptible to affect Cory's shearwater population dynamics for long periods would occur. Although our best model considered adult survival to be time-dependent, we did not introduce temporal variability of adult survival rate in our stochastic models. Indeed (see e.g., Gould and Nichols, 1998), the observed temporal variability of adult survival results from sampling variability (related to capture-recapture effort and to the number of individuals that die every year) and from actual temporal variability (caused by environmental stochasticity). When calculating the latter parameter (following Gould and Nichols, 1998), we found a negative value (−0.0253) and under these conditons, Gould and Nichols (1998) state that the actual temporal variability of adult survival is null or extremely small. Finally, we chose to use a single-state model (CJS), and not a multi-state one, to estimate transition probabilities on Vila islet (Appendix B).

Concerning breeding probabilities, Sanz-Aguilar et al. (2011) managed to account for the probability to take sabbatical years when determining recapture probabilities. In their study, however, these authors considered that all recaptured individuals were breeders (and therefore, that non-breeders were not recaptured), and they missed a few burrows in their study colony each year. In contrast, we recaptured a non-negligible proportion of non-breeders each year and we always managed to inspect all the burrows in our study plot. Therefore, the method of Sanz-Aguilar et al. (2011) is unlikely to be suitable to our data. Given that, furthermore, (1) we managed to determine the breeding status (breeder or non-breeder) of our study birds in 96% of cases and (2) our goal here was to assess global population trends and not to determine the causes of the inter-annual variations in $P_{B\rightarrow B}$ or $P_{NB\rightarrow NB}$, we believe that using a single-state model will not introduce a significant bias in our results.

Bearing these caveats in mind, our results show that in the absence of rescue campaigns and when setting $P_{B\rightarrow B}$ to the value observed on Vila islet, the Azorean population of Cory's shearwaters should decline, unless we use unrealistically high values (see below) of juvenile survival in our simulations. Note that since the population was declining ($\lambda < 1$) in most of our simulations, we did not introduce density-dependence in our models. Since, however, breeding densities on the main islands may be lower than on Vila islet, we re-did our simulations after setting $P_{B\rightarrow B}$ to 0.9 on the main islands (see Section 2). Under these conditions, apparently realistic values of juvenile survival should allow population stability, regardless of poaching and light-induced mortality levels.

However, the actual juvenile survival rate in the Azores remains unknown. On the mammal-free Vila islet, where no light-induced mortality occurs, a juvenile survival rate of 0.545 would allow population stability. Because this value is not too far from the estimate concerning the population from the Lavezzi islands (0.52; Jenouvrier et al., 2008), it does not seem *a priori* too unrealistic. Although this value should allow Cory's shearwaters numbers to increase on the main islands if $P_{B\rightarrow B} = 0.9$, it is insufficient to allow population stability if $P_{B\rightarrow B} = 0.781$, even in the absence of light-induced mortality and poaching (Appendix D). When considering the juvenile survival rates used in our simulations, and given that introduced predators occur on the main islands, values of breeding success compatible with both the presence of alien predators and population stability are observed only when rescue campaigns occur, except when $P_{B\rightarrow B} = 0.9$ and juvenile survival is extremely (and most probably unrealistically as well, see Section 4.2.3) high (Table 2).

4.1. Effect of light-induced mortality on population trends

Although the sources of artificial lights that affect seabirds have long been identified, only one study (Simons, 1984) had previously modelled the consequences of light-induced mortality for petrel population viability. Urban mortality affects at least 21 petrel species (review in e.g., Reed et al. (1985)), some of which appear especially vulnerable due to their reduced numbers or endemism level (Montevecchi, 2006). The impact of urban lights can be much higher than in the Azores, concerning between 20% and 40% of fledglings in Barau's petrel (*Pterodroma baraui*), a species endemic to Réunion island (Le Corre et al., 2002) and considered 'Endangered' (BirdLife International, 2010), and over 50% in the 'Endangered' (BirdLife International, 2010) Newell's shearwater (*Puffinus newelli*) on Kauai island, Hawaii (Reed et al., 1985), and in the Cory's shearwaters from Tenerife island, Canary islands (Rodríguez and Rodríguez, 2009).

In the Azores, light-induced mortality varied among islands, so that predicted trends also depended on the island. Thus, a juvenile survival of 0.6 (possible in a strongly increasing Cory's shearwater population; Mougin et al., 1990) might allow population growth on several of the main islands in the absence of rescue campaigns (Appendix D). At the Azores scale, however, our simulations showed that in the absence of a strong increase in breeding success and/or of a very high juvenile survival, rescue campaigns should only slow down the decline if breeding probabilities are similar to those observed on Vila islet. In contrast, if possible lower competition for nests than on Vila islet allows adults to breed almost every year on the main islands, rescue campaigns should allow reverting the trends provided that juvenile survival equals or exceeds 0.491. In addition, not all the grounded fledglings are found and some persons rescue and release birds without informing the Environment Department from the Azores or the researchers, so that our estimates of light-induced mortality must be considered as minimal ones. Note that our results also show that urban mortality affects population dynamics much more than does poaching mortality.

In Cory's shearwater (Rodríguez and Rodríguez, 2009; this study), as in many other petrel species (review in Montevecchi (2006), Miles et al. (2010); but see Luzardo et al. (2008); Rodríguez and Rodríguez (2009)) the bulk of grounded birds are fledglings, so that experience might play an important role in the sensitivity to urban lights (Montevecchi, 2006).

4.2. Do other factors affect population dynamics?

To determine the part played by light-induced mortality in the dynamics of the Azorean population of Cory's shearwaters as reliably as possible, it is necessary to examine all the factors that can affect the different demographic parameters.

4.2.1. Factors affecting adult survival rate

Sensitivity analyses confirmed that adult survival rate is the parameter that has the greatest influence on population growth rate in Cory's shearwater, as it typically does in long-lived species (Sæther and Bakke, 2000). Therefore, a slight decrease in adult survival will have more dramatic consequences for population dynamics than a stronger decrease in fecundity.

At sea, fishery mortality has been shown to be responsible for population declines and/or low survival rates in many procellariiformes (see Introduction), including Mediterranean Cory's shearwaters (Belda and Sánchez, 2001; Cooper et al., 2003; BirdLife International, 2004; Jenouvrier et al., 2009). Conversely, Granadeiro et al. (2006) estimated that fishery mortality was not severe enough to depress Cory's shearwater numbers on the Salvages islands.

In the Azores area, Cory's shearwaters do not appear to be victim of fisheries during the breeding period (data from the 'POPA' Program), and so far as we know, no fishery mortality has been reported from more northerly latitudes in the Atlantic, where Azorean breeders regularly forage (Magalhães et al., 2008; Paiva et al., 2010). During the non-breeding period, and given that the different populations of Atlantic Cory's shearwaters share the same wintering areas (Mougin et al., 1988; Monteiro et al., 1996a; González-Solís et al., 2007), the population from the Azores should suffer low fishery mortality in the southern Atlantic as well. The adult survival rate on Vila islet was considerably higher than in most Mediterranean populations and similar to that observed on the Salvages islands (Mougin et al., 2000; Igual et al., 2009; Jenouvrier et al., 2009), supporting this hypothesis (at least when considering adults). Additional support comes from the absence of Cory's shearwater from the by-catch lists of the fishing vessels operating off Brazil and southern Africa (pelagic and demersal fisheries; Bugoni et al., 2008b; Petersen et al., 2009a,b), even though some individuals are regularly killed by the crew operating in Brazilian small-scale fisheries, who hit them when they come too close to their fishing boats (Bugoni et al., 2008a).

However, adult survival in the Azores was estimated in a population breeding on an islet free of introduced predators and uninhabited, contrary to the nine main islands where some adult and subadult Cory's shearwaters are regularly victim of vehicles and dogs, and occasionally of vandalism (V.C. Neves, pers. comm.; this study). Preliminary data suggest that such mortality does not exceed a few tens of individuals per year on each island, but a more accurate assessment is needed. In any case, however, adult and pre-breeder survival on the nine main Azorean islands might be very slightly lower than on Vila islet.

4.2.2. Factors affecting chick productivity

Breeding success on Vila islet between 2002 and 2008 was slightly higher than on the main islands from the Azores which hold alien predators, and it was also considerably lower than at some mammal-free locations in the Mediterranean where it exceeds 70% (Ristow et al., 1991; Thibault, 1995). Although estimates of food availability *per capita* in the Mediterranean and in the Atlantic are lacking, the regular alternation of long and short foraging trips by the Cory's shearwaters from the Azores during the chick-rearing period (Magalhães et al., 2008; Paiva et al., 2010) strongly suggests that food availability near the Azorean islands during this period is poor (see Granadeiro et al. (1998)). Despite this, the daily food intake of chicks and the breeding success in the Azores are similar to those on the Salvages islands (breeding success there is 0.566; Mougin et al., 2000) where food availability is sufficient to allow adults not to use a bi-modal foraging strategy, except during the years of poorest food availability (Magalhães et al., 2008).

Therefore, the main factor affecting chick productivity in the Azores, including at mammal-free locations, might be the conditions on land rather than food availability during the breeding period. Supporting this, competition for nests on Vila islet, which is extremely strong, regularly results in some egg and chick losses (Monteiro et al., 1996b; Ramos et al., 1997; this study), whereas the low breeding success on the Salvages islands (Mougin et al., 2000) may be due to the presence of many young, inexperienced breeders at this locality (Mougin et al., 2000). Further support also comes from the strong inter-annual and inter-colony variability of the impact of introduced mammals on Cory's shearwater breeding success (Thibault, 1995). In the Azores, breeding success on Corvo island is very low due to the impact of introduced predators (40.1%, $n = 182$ nests; Henriques, 2010), whereas it can be similar to that observed some years on Vila islet at the colony from Capelo (62.2%, $n = 45$ nests; J. Bried, unpubl. data) which is situated on Faial island a few kilometres far from Morro de Castelo Branco. Being intermediate between those from Corvo and Capelo, the estimate of Tamagnini Mendes (2008) is compatible with a "moderate" predation pressure. For this reason, and although it was obtained from only nine nests, we decided to use it in our simulations concerning the main islands.

4.2.3. Factors affecting juvenile survival

During rescue campaigns, some recaptures occurring several days after release but at locations far from the release site, including on other islands of the archipelago, show that juvenile Cory's shearwaters can remain in the Azores area during the first few days after fledging. Although the incidence of such behaviour remains unknown, low food availability in the Azores area during the chick-rearing period (see above) means that juveniles might have difficulties in obtaining food if they remain in the Azorean waters at the start of the post-fledging period, especially when considering that there is no post-fledging parental care in petrels (Brooke, 2004).

Furthermore, the decrease in oceanic productivity observed in recent years might result in increased difficulties for seabirds to obtain food (review in e.g., Grémillet and Boulinier, 2009). Supporting this, breeding success on Vila islet reached 0.74 in 1994 (Monteiro et al., 1996a), whereas it has never exceeded 0.69 since the beginning of our demographic study. Under these conditions, only experienced individuals, which are supposed to be the most efficient foragers (Lack (1968); for procellariiformes, see e.g., Weimerskirch, 1990, 1992), might be able to cope with this situation, contrary to juveniles, a high proportion of which would die from starvation (Nelson, 1980). Both hypotheses, which are not mutually exclusive, suggest that Azorean Cory's shearwaters might have a low juvenile survival rate, perhaps not exceeding that observed in their Mediterranean conspecifics (0.52; Jenouvrier et al., 2008).

4.2.4. Factors affecting age at first breeding

In the Azores, Cory's shearwaters are now restricted to main island cliffs and mammal-free islets due to the presence of introduced predators on the main islands (Monteiro et al., 1996b), where nest availability may not be as limited as on Vila islet. Nonetheless, age at first breeding should not (at least in the short term, as long as conditions on land do not change) be younger than that used in our simulations, which was determined in a recovering population (Mougin et al., 2000), that is, in a population where nest availability was not a limiting factor either. Note, however, that when simulations were conducted using 7.9 years instead of 8.9 years, we obtained similar results concerning global population trends (data not shown).

4.3. What can be done to slow down (or revert) the decline?

Our results, associated with the fact that adult survival might be slightly lower on the main islands than on Vila islet and that light-induced mortality is probably underestimated, cannot allow ruling out the hypothesis that Cory's shearwater numbers in the Azores are decreasing, especially when considering that (1) stochastic growth rates are probably slightly lower than the corresponding deterministic growth rates (see Samaranayaka and Fletcher, 2010), and (2) weaker competition for nests than on Vila islet might allow lower-quality individuals to breed on the main islands, perhaps resulting in lower mean adult survival rates at main island colonies (see Tavecchia et al., 2008). Unfortunately, estimates of adult survival and breeding probabilities $P_{B \rightarrow B}$ on the main islands are lacking, preventing us from drawing firm conclusions.

Since we found a high adult survival rate, we can be confident that an eventual decline would be attributable essentially to a low proportion of eggs resulting in a young that will reach adulthood. Therefore, it is necessary to improve breeding success and juvenile survival, especially when considering that after adult and pre-breeder survival, fecundity is the most important demographic parameter affecting the dynamics of the Azorean Cory's shearwater population (Table 1). To do this, the most efficient and cost-effective measure appears to be reducing light-induced mortality. It is necessary to continue rescue campaigns, which allow reducing observed urban mortality by almost 93%. Interestingly, this percentage is similar to that observed for the rescue campaigns of Cory's shearwater fledglings on Tenerife island (Rodríguez and Rodríguez, 2009) and for other rescue campaigns concerning other petrel species at other localities (Telfer et al., 1987; Le Corre et al., 2002; Miles et al., 2010). Simultaneously, light pollution should be reduced by shielding, modifying light wavelengths, and using intermittent lights (rather than steady rotating beams) at lighthouses (review in Montevecchi (2006)).

However, reducing light-induced mortality alone should be insufficient to revert the decline in the Azores, unless juvenile survival during the first year at sea is sufficiently high. Since improving juvenile survival by artificially increasing food availability at sea is unrealistic (or at least, should prove extremely difficult), we recommend taking steps aimed at increasing chick productivity before fledging. The area of the main islands precludes the eradication of the introduced predators, except perhaps at some locations. Control operations can and should be conducted, but habitat conditions at the colonies must be considered when establishing protocols (e.g., Igual et al., 2006) and they need to be repeated each year. If efficient control cannot be achieved, establishing fenced mammal-free areas can represent a valuable solution (Micol and Jouventin, 1995). We also recommend installing artificial nests on mammal-free islets, which will allow an increase not only in shearwater breeding numbers (Ramos et al., 1997), but perhaps also in breeding success (see Bried et al., 2009). Finally, poaching of chicks should be prevented more efficiently.

Although the adult Cory's shearwaters from the Azores do not seem to suffer heavy fishery mortality, adult survival is the parameter whose variations have the greatest influence on the population dynamics of the species (Table 1). This remains true when the eradication of introduced predators allows improving breeding success (Igual et al., 2009). Therefore, adult mortality on the main islands should be reduced as much as possible by limiting vehicle speed on the roads situated near colonies. It is also desirable to determine the number and the age ratio of the individuals killed by Brazilian fishermen. Finally, and in order to improve the efficiency of the measures proposed here, we recommend continuing and improving awareness campaigns, especially by targeting Brazilian fishermen as well. Obviously, the set of measures proposed here does not only hold for the Azores, but for any locality where petrels suffer mortality from urban lights, alien predators and man.

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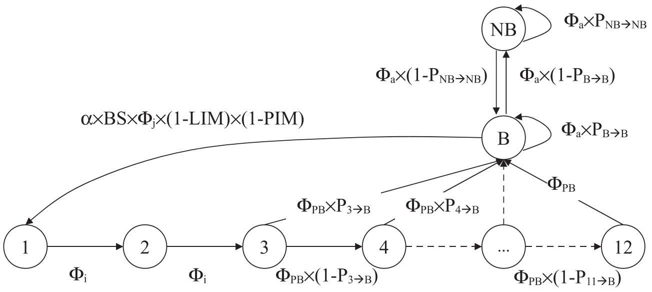
Appendix A

Representation of Cory's shearwater life cycle. Age classes 1 and 2 are immature birds, age classes 3–12 are pre-breeders. From 13 years old onwards, all the birds are considered to have recruited into the breeding population (B: breeders). Adults can skip breeding years and become non-breeders (NB).



Appendix B

Breeding probabilities of Cory's shearwaters in the Azores (calculated from Mougin et al., 2000, except for $P_{B\rightarrow B}$ and $P_{NB\rightarrow NB}$ calculated from our demographic survey on Vila islet).

	Breeding probability
$P_{3\rightarrow B}$	0.003
$P_{4\rightarrow B}$	0.005
$P_{5\rightarrow B}$	0.070
$P_{6\rightarrow B}$	0.169
$P_{7\rightarrow B}$	0.298
$P_{8\rightarrow B}$	0.343
$P_{9\rightarrow B}$	0.522
$P_{10\rightarrow B}$	0.530
$P_{11\rightarrow B}$	0.677
$P_{B\rightarrow B}$	0.781
$P_{NB\rightarrow NB}$	0.557

Appendix C

Determining the annual adult survival rate of Azorean Cory's shearwaters: models were ranked according to AICc (second-order Akaike's information criterion). The best model appears in bold.

Model	No of parameters	Deviance	AICc	ΔAICc
$\Phi(t)$, p$(m+t)$	**12**	**1178.6963**	**1203.0299**	**0.00**
$\Phi(t)$, p$(m+g+t)$	14	1176.0251	1204.4752	1.45
$\Phi.$, p$(m+t)$	8	1190.0863	1206.2397	3.21
$\Phi(g+t)$, p$(m+g+t)$	15	1175.8640	1206.3791	3.35
$\Phi(g+t)$, p$(m+t)$	14	1178.5854	1207.0356	4.01
$\Phi.$, p$(m+g+t)$	9	1189.2063	1207.3982	4.37
$\Phi(g)$, p$(m+t)$	9	1190.0675	1208.2594	5.23
$\Phi(g)$, p$(m+g+t)$	10	1188.6644	1208.8992	5.87
$\Phi(t)$, p$(m+g*t)$	19	1173.6164	1212.4354	9.41
$\Phi(g*t)$, p$(m+t)$	18	1177.4704	1214.2067	11.18
$\Phi(g+t)$, p$(m+g*t)$	20	1173.5057	1214.4119	11.38
$\Phi.$, p$(m+g*t)$	14	1186.0011	1214.4512	11.42
$\Phi(g*t)$, p$(m+g+t)$	20	1174.6558	1215.5620	12.53
$\Phi(g)$, p$(m+g*t)$	15	1185.8778	1216.3928	13.36
$\Phi(g*t)$, p$(m+g*t)$	23	1171.9529	1219.1477	16.12
$\Phi(t)$, p(m)	8	1211.5005	1227.6539	24.62
$\Phi(t)$, p$(m+g)$	9	1210.4892	1228.6811	25.65
$\Phi(g+t)$, p(m)	9	1211.4902	1229.6821	26.65
$\Phi.$, p(m)	3	1224.1515	1230.1769	27.15
$\Phi(g+t)$, p$(m+g)$	10	1210.2979	1230.5327	27.50
$\Phi.$, p$(m+g)$	4	1222.8607	1230.9031	27.87
$\Phi(g)$, p(m)	4	1224.1036	1232.1461	29.12
$\Phi(g)$, p$(m+g)$	5	1222.2920	1232.3556	29.33
$\Phi(g*t)$, p(m)	14	1210.4620	1238.9122	35.88
$\Phi(g*t)$, p$(m+g)$	15	1208.4324	1238.9474	35.92

Appendix D

Results of deterministic models concerning the growth rates of the Azorean population of Cory's shearwaters (modelling was conducted using $P_{B\rightarrow B} = 0.781$, except for the values in brackets where $P_{B\rightarrow B} = 0.9$).

Appendix D

	Corvo	Flores	Graciosa	Faial	Pico	S. Jorge	Terceira	S. Miguel	Sta Maria	Vila	Azores[a]
No of breeding pairs	22,980	14,981	13,312	14,728	23,897	36,360	9975	40,259	12,254	400	188,000
No of fledglings produced (NP)	9776	6373	5663	6265	10,166	15,467	4243	17,126	5213	170	79,974 (95,481)
No of victims from urban lights (NV)	65	96	421	1236	1547	917	199	526	160	0	5167
No of released individuals	65	91	399	1187	1424	828	199	443	152	0	4788
LIM without *SOS Cagarro* (LIM)	0.0066	0.0151	0.0743	0.1973	0.1522	0.0593	0.0469	0.0307	0.0307[b]	0	0.0646 (0.0541)[b]
LIM with *SOS Cagarro* ($\mathrm{LIM_{sos}}$)	0	0.0008	0.0039	0.0078	0.0121	0.0058	0	0.0048	0.0015[b]	0	0.0047(0.0040)[b]
Population growth rate (*λ*)											
Without urban mortality[c]											
$\Phi_j = 0.4$	0.985137	0.985137	0.985137	0.985137	0.985137	0.985137	0.985137	0.985137	0.985137	0.987139	0.985137 (0.992190)
$\Phi_j = 0.5$	0.994007	0.994007	0.994007	0.994007	0.994007	0.994007	0.994007	0.994007	0.994007	0.996257	0.994007 (1.001790)
$\Phi_j = 0.6$	1.002040	1.002040	1.002040	1.002040	1.002040	1.002040	1.002040	1.002040	1.002040	1.004500	1.002040 (1.010410)
With $\mathrm{LIM_{sos}}$											
$\Phi_j = 0.4$	0.985137	0.985107	0.984991	0.984845	0.984683	0.984920	0.985137	0.984958	0.985081		0.984961 (0.992027)
$\Phi_j = 0.5$	0.994007	0.993974	0.993843	0.993678	0.993496	0.993763	0.994007	0.993805	0.993944	–	0.993809 (1.001610)
$\Phi_j = 0.6$	1.002040	1.002010	1.001860	1.001680	1.001480	1.001780	1.002040	1.001820	1.001970		1.001830 (1.010210)
With LIM											
$\Phi_j = 0.4$	0.984890	0.984570	0.982309	0.977401	0.979235	0.982888	0.983363	0.983980	0.983980		0.982684 (0.989958)
$\Phi_j = 0.5$	0.993789	0.993369	0.990820	0.985264	0.987344	0.991473	0.992009	0.992705	0.992705	–	0.991243 (0.999297)
$\Phi_j = 0.6$	1.001740	1.00135	0.998552	0.992445	0.994735	0.999268	0.999856	1.000620	1.000620		0.999016 (1.007700)
Minimum poaching mortality (500 chicks/year: $\mathrm{PIM_{min}}$)	–	–	–	–	–	–	–	–	0.0959	–	0.0063 (0.0052)
LIM considering the number of fledglings after accounting for $\mathrm{PIM_{min}}$	–	–	–	–	–	–	–	–	0.0339	–	0.0650 (0.0544)
$\mathrm{LIM_{sos}}$ considering the number of fledglings after accounting for $\mathrm{PIM_{min}}$	–	–	–	–	–	–	–	–	0.0017	–	0.0048 (0.0040)
Maximum	–	–	–	–	–	–	–	–	0.2877	–	0.0188 (0.0157)

(*continued on next page*)

Appendix D (*continued*)

	Corvo	Flores	Graciosa	Faial	Pico	S. Jorge	Terceira	S. Miguel	Sta Maria	Vila	Azores[a]
poaching mortality (1500 chicks/year: PIM_{max})											
LIM considering the number of fledglings after accounting for PIM_{max}	–	–	–	–	–	–	–	–	0.0431	–	0.0658 (0.0550)
LIM_{sos} considering the number of fledglings after accounting for PIM_{max}	–	–	–	–	–	–	–	–	0.0022	–	0.0048 (0.0040)
Population growth rate (λ)											
LIM, PIM_{min}											
$\Phi_j = 0.4$	–	–	–	–	–	–	–	–	0.980260		0.982441 (0.989740)
$\Phi_j = 0.5$	–	–	–	–	–	–	–	–	0.988504	–	0.990969 (0.999053)
$\Phi_j = 0.6$	–	–	–	–	–	–	–	–	0.996011		0.998716 (1.007440)
LIM_{sos}, PIM_{min}											
$\Phi_j = 0.4$	–	–	–	–	–	–	–	–	0.981408		0.984722 (0.991815)
$\Phi_j = 0.5$	–	–	–	–	–	–	–	–	0.989802	–	0.993540 (1.001370)
$\Phi_j = 0.6$	–	–	–	–	–	–	–	–	0.997436		1.001530 (1.009960)
LIM, PIM_{max}	–										
$\Phi_j = 0.4$	–	–	–	–	–	–	–	–	0.972257		0.981957 (0.989298)
$\Phi_j = 0.5$	–	–	–	–	–	–	–	–	0.979404	–	0.990423 (0.998559)
$\Phi_j = 0.6$	–	–	–	–	–	–	–	–	0.985971		0.998117 (1.006900)
LIM_{sos}, PIM_{max}											
$\Phi_j = 0.4$	–	–	–	–	–	–	–	–	0.973525		0.984253 (0.991387)
$\Phi_j = 0.5$	–	–	–	–	–	–	–	–	0.980852	–	0.993011 (1.000890)
$\Phi_j = 0.6$	–	–	–	–	–	–	–	–	0.987575		1.000950 (1.009440)

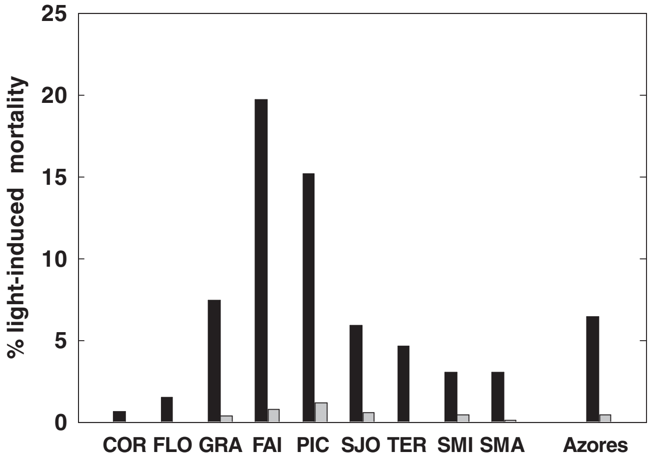
[a] Population size estimates: for the Azores archipelago, BirdLife International (2004); for each island, calculated from L.R. Monteiro and R.S. Feio in Bolton (2001a,b).

[b] Without accounting for poaching-induced mortality.

[c] Since population size does not influence deterministic growth rates, the latter were the same when considering each island separately or the whole archipelago.

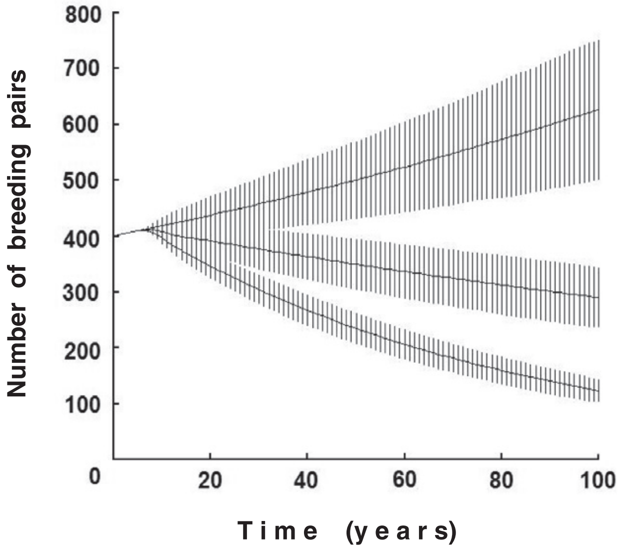
Appendix E

Proportion of fledglings lost due to light pollution on each island and at the archipelago's scale, without accounting for poaching mortality. Black bars shows LIM and grey bars represents LIM_{sos}. COR = Corvo, FLO = Flores, GRA = Graciosa, FAI = Faial, PIC = Pico, SJO = São Jorge, TER = Terceira, SMI = São Miguel and SMA = Santa Maria. $P_{B\rightarrow B}$ was set to 0.781.



Appendix F

Mean stochastic population trajectories of the Cory's shearwater population from Vila islet with 2 SD confidence intervals (bars). From the top to the bottom, lines correspond to Φ_j = 0.6, 0.5 and 0.4, respectively.



Appendix G

Results of the stochastic modelling of the dynamics of the Cory's shearwater population from the main Azores islands and from Vila islet (in brackets) when determining extinction time and the breeding numbers at time $t_{0+100\text{years}}$, with respect to juvenile survival, light-induced mortality and poaching. Estimates are given ± SE and $P_{B\rightarrow B}$ = 0.781.

	Extinction time (years)	Estimated breeding numbers (pairs) at time $t_{0+100\text{years}}$
LIM = 0, PIM = 0		
Φ_j = 0.4	838.6 ± 0.2 (496.2 ± 0.5)	41980 ± 50 (109.5 ± 0.3)
Φ_j = 0.5	2098.0 ± 1.0 (1713.2 ± 3.5)	102900 ± 131 (275.0 ± 0.8)
Φ_j = 0.6	–	230100 ± 311 (626.8 ± 2.0)
LIM_{sos}, PIM = 0		
Φ_j = 0.4	828.6 ± 0.2	41230 ± 48
Φ_j = 0.5	2030.4 ± 1.0	100800 ± 129
Φ_j = 0.6	–	225200 ± 304
LIM, PIM = 0		
Φ_j = 0.4	718.0 ± 0.2	32720 ± 37
Φ_j = 0.5	1431.9 ± 0.6	77860 ± 97
Φ_j = 0.6	12756.8 ± 15.6	170000 ± 225
LIM = 0. PIM_{min}		
Φ_j = 0.4	825.3 ± 0.2	40970 ± 48
Φ_j = 0.5	2008.6 ± 1.0	100200 ± 128
Φ_j = 0.6	–	223500 ± 302
LIM_{sos}, PIM_{min}		
Φ_j = 0.4	815.4 ± 0.2	40240 ± 47
Φ_j = 0.5	1945.6 ± 0.9	98140 ± 125
Φ_j = 0.6	–	218700 ± 295
LIM, PIM_{min}		
Φ_j = 0.4	707.8 ± 0.2	31910 ± 36
Φ_j = 0.5	1388.1 ± 0.5	75730 ± 94
Φ_j = 0.6	9786.1 ± 10.4	165100 ± 218
LIM = 0. PIM_{max}		
Φ_j = 0.4	799.9 ± 0.2	39070 ± 46
Φ_j = 0.5	1850.9 ± 0.9	94960 ± 121
Φ_j = 0.6	–	210900 ± 284
LIM_{sos}, PIM_{max}		
Φ_j = 0.4	790.7 ± 0.2	38370 ± 45
Φ_j = 0.5	1797.5 ± 0.8	93050 ± 118
Φ_j = 0.6	–	206400 ± 277
LIM, PIM_{max}		
Φ_j = 0.4	688.5 ± 0.2	30380 ± 35
Φ_j = 0.5	1308.3 ± 0.5	71680 ± 89
Φ_j = 0.6	6679.8 ± 5.9	155400 ± 205

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