Demography of the critically endangered Balearic shearwater: impacts of fisheries and time to extinction

Meritxell Genovart[1] m.genovart@uib.es

Jose Manuel Arcos[2] jmarcos@seo.org

David Álvarez[1] dalvarezf@gmail.com

Miguel McMinn[3] miguel.mcminn@gmail.com

Rhiannon Meier[4] Rhiannon.Meier@noc.soton.ac.uk

Russell Wynn[4] rbw1@noc.ac.uk

Tim Guilford[5] tim.guilford@zoo.ox.ac.uk

Daniel Oro[1] d.oro@uib.es

[1] Population Ecology Group, IMEDEA (CSIC-UIB), Miquel Marquès 21, 07190 Esporles, Mallorca, Spain

[2] SEO/BirdLife, Delegació de Catalunya, C/ Murcia 2-8, Local 13, 08026 Barcelona, Spain

[3] Balearic Shearwater Conservation Association, Puig Teide 4, Palmanova 07181, Spain

[4] Marine Geoscience Group, National Oceanography Centre, Southampton, UK

[5] Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK

Corresponding author: Meritxell Genovart; Phone: 34 971611929; Fax: 34 971611761

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Summary

1. The Balearic shearwater *Puffinus mauretanicus* is the most endangered European seabird, and a decade ago the time to extinction was estimated at only ~40 years. As with many marine predators, the species is affected by commercial fishing in opposing ways: as a source of mortality from bycatch, and also by providing discards as a predictable and abundant food resource.

2. Since the previous assessment in 2004, new demographic and population data have become available, more sophisticated demographic modelling has been developed, and new fishing policies from the European Union (CFP) will apply, posing different scenarios for the viability of the Balearic shearwater. So there is an urgent need for a more reliable update of the conservation status of the species.

3. Demographic data were collected between 1985 and 2014 at one of the world's largest colonies. Most demographic parameters were estimated using multi-event capture-recapture modelling. Some parameters, such as bycatch probability, immature survival and recruitment were estimated for the first time. We incorporated estimates into stochastic population models to assess viability and the forecast time to extinction under different management scenarios, accounting for upcoming fishing policies.

4. Adult survival was much lower (0.813, SE: 0.013) than expected, and largely influenced by bycatch, which accounted for a minimum of 0.45 (SE: 0.231) of total mortality. Survival estimate must be taken as conservative, as our study colony was free of invasive predators. Breeding success was positively correlated with discard availability. Recruitment started at low rates in 3-year old birds (0.037, SE: 0.056), increased sharply in following age classes and was almost complete at 6 years of age. Under the present scenario of bycatch mortality and discards availability, we predict a time to extinction of 63 years (95% CI: 61-65).

5. *Synthesis and applications*. Population projections suggest that impact of fisheries is unsustainable. The buffering of higher breeding success and fast recruitment seems limited because of the low influence of these parameters on

population growth rate. Nevertheless, imminent discard bans under new CFP may accelerate the declining trend. This study shows that urgent mitigation measures are needed to minimize the impact caused by bycatch mortality in fisheries.

Keywords: conservation, bycatch, discards, environmental policies, marine predators, multi-event capture-recapture, population models, survival.

Introduction

Effective management of species, especially for threatened taxa, should begin by estimating with accuracy their demographic parameters in order to assess population growth rate, elaborate a conservation diagnosis and make predictions about the fate of a population (Caswell 2001; Morris & Doak 2002). More importantly, conservation-oriented science informs managers about what demographic parameters are unsustainable, aiding optimization of priority actions and ensuring efforts are concentrated on those parameters to be remedied (e.g. Norris 2004). This is essential when dealing with endangered species, because time to reverse sharp declining trends is limited and good management should target the most effective actions. However many of those endangered species are neither abundant nor widespread, and surveillance monitoring typically provides weak inferences about population declines.

This is the case for the Balearic shearwater *Puffinus mauretanicus*, the most threatened seabird in Europe and listed as critically endangered, the highest IUCN threat category for a taxa in the wild (BirdLife International 2015). Balearic shearwaters breed in mostly inaccessible sites, so it is unfeasible to monitor population trends using counts, abundance indexes or similar techniques. Categorization of the species was made 10 years ago using scattered demographic information applied to a population viability analysis (PVA) that predicted a mean extinction time of only ~40 (Oro *et al.* 2004). Since that assessment, new demographic and population data have become available, more sophisticated demographic modelling has been developed, and new fisheries policies from the European Union introduced (CFP); these changes pose a different future scenario for the Balearic shearwater and highlight the urgent need for a more reliable update of its conservation status.

The census of the breeding population was recently updated to ~3,200 pairs, a much larger figure than the previous estimate of 2,000 pairs. Recent at-sea and coastal-based surveys suggest a global population in the range of 20,000-30,000 individuals (Arcos 2011; Arcos *et al.* 2012; Arroyo *et al.* 2014). These new figures make necessary a reassessment of the conservation status of the species, but to do it properly also survival estimates should be updated, and bycatch mortality quantified (Oro *et al.* 2004; ICES 2013). Incidental capture or bycatch represents ~8% of global fisheries production (Kelleher 2005) and is a major threat for seabirds, particularly for the Procellariiforms (Anderson *et al.* 2011, Croxall et al. 2012), and the Balearic shearwater is no exception (Cooper *et al.* 2003; Laneri *et al.* 2010; ICES 2013). Conversely, there is also evidence that Balearic shearwaters also reap some benefit from fisheries through discard scavenging, e.g. (Arcos & Oro 2002) found that >40% of the energy requirements of Balearic shearwaters during the breeding season came from trawler discards. The increase in food availability provided by discards (and their high predictability in space and time) seems to be responsible for the growth of many seabird populations, mediated by a positive effect on reproductive success and probably also survival (Oro *et al.* 2013). However, forthcoming CFP regulations, aimed at banning discard practices, could negatively influence the breeding performance of the species, at least in the short term (Bicknell et al. 2013). More positively, bycatch mortality is expected to decrease in the future, as increasing awareness leads to mitigation action through a specific Plan of Action (see Table S3).

We used historical ringing and recovery data collected between 1985 and 2014, and new at-sea estimates of population size to (i) update adult survival probability and estimate for the first time: immature survival, recruitment probability by age, and the probability of dying in fishing gears, by using multi-event capture-recapture modelling; (ii) estimate breeding success and assess the influence of fishing discards on this parameter; and (iii) construct population models for assessing the probability of extinction under several scenarios considering the contrasting effects of fisheries. While Oro *et al.* (2004) used a limited number of years to estimate demographic parameters, the present study uses recently developed capture-recapture models that allowed us to exploit a much larger data set covering 30 years of monitoring.

Methods

STUDY AREA AND FIELD METHODS

Data were collected at Sa Cella cave (Mallorca), one of the largest colonies of the species (~170-200 breeding pairs), between 1985 and 2014, except for the period 2005-2009, when the colony was not monitored. The colony is free of carnivores and rats, and legally protected.

Adults and chicks were trapped by hand, marked with stainless-steel rings with a unique code (see details in Oro *et al.* 2004) and their breeding status assigned (either breeder or unknown). Recoveries were obtained from the Spanish ringing office (SEO/BirdLife) and provided by fishermen, researchers and wildlife recovery centres. Each recovery was assigned as caused by fishing longlines (carrying a hook) or unknown.

ANALYSIS OF DEMOGRAPHIC PARAMETERS

To estimate survival, recruitment and probability of dying in fishing gears, we used multi-event capture-recapture modelling (Pradel 2005). These models hold two levels in capture-recapture data: the field observations, called “events”, which are encoded in the capture histories, and the “states”, another level of data that can only be inferred. The “states” would be defined depending on the biological question to answer. The states changed over time according to a Markov process and the events were generated from the states on each occasion (Genovart, Pradel & Oro 2012). Models were fitted in program E-SURGE (Choquet, Rouan & Pradel 2009), which distinguishes three basic types of parameters: the initial state probabilities, the transition probabilities between states, and the event probabilities. Model selection relied on QAICc, i.e. the Akaike Information Criterion corrected for overdispersion and for small sample sizes (Burnham & Anderson 2002).

Owing that there is no goodness-of-fit test available for multi-event models, we assessed the fit of a model that only retains whether an individual is encountered or not (Cormack-Jolly-Seber type models) using U-care (Choquet *et al.* 2009).

Given the capture-recapture effort was no uniform during all study years, we initially performed an analysis with a reduced dataset containing no data collection gaps, to extract reliable estimates of age at recruitment (*Recruitment analysis*). We subsequently carried out a second analysis on the complete dataset, and fixed age of recruitment to estimate both immature and adult survival, and the probability of fisheries-related mortality (*Global analysis*). We distinguished between breeder and non-breeder survival, because those not observed as breeders may be transients, and therefore artificially reduce estimated local survival rates. Our model incorporated an error probability of ascertaining an individual's breeding status, i.e. the probability that a breeder was not observed to be breeding.

Recruitment analysis

Using data from 1994-2004, we classified individuals into two groups based on the age at first capture (chicks and adults). Models included three biological states: alive breeder (B), alive non-breeder (NB) and dead (D). The last state was not observable and the initial state in our models was always NB in animals marked as chicks. Transitions between states were modelled in a two-step approach: survival and recapture probability. In each capture-recapture occasion ('*t*') we considered 3 possible events: individual not seen (noted 0), individual seen alive but with unknown breeding status (noted 1) and individual seen breeding (noted 2). Recruitment was defined as the probability r_i of breeding for the first time at each age i and equalled the transition between state non-breeder to breeder. As birds do not visit the colony before being 3 years old (Oro *et al.* 2004, own data), survival was modelled separately for both immature (1 and 2 year old) and adults (for breeders and non-breeders), and was kept constant in all models. We also undertook a model run to test whether survival of immature was equivalent to non-breeding adults. Then, we tested several models considering different age curves at recruitment, starting at 3 years old and with full recruitment from 3 to ≥7 years old. We had no power to test for longer age curves of recruitment, although results suggested that recruitment at older ages was likely rare.

Global analysis

We analysed all data available from 1985 to 2014 and, as previously, individuals were classified in two groups based on their age at first capture. Models included five biological states: alive breeder (B); alive non-breeder (NB); individual recently dead by longline bycatch (RF); individual recently dead by unknown causes (RD); and dead (D), this last state being non-observable. The initial state in our models was always NB for chicks, and individuals younger than 3 years old were never observed. Transitions between states were modelled in a three-step approach: survival, recruitment probability and probability of death in bycatch events (conditional on survival). In each capture-recapture occasion ('*t*') we considered five possible events: Individual not seen (noted 0); individual seen not breeding (noted 1); individual seen breeding (noted 2); individual found recently dead by bycatch (noted 3); individual found recently dead by unknown causes (noted 4).

As in the Recruitment analysis, we assumed two different survivals: immature and adult, the latter considering different survival for breeders and non-breeders. Given that only ringing (but not recapture) was carried out from 1985 to 1996, we estimated survival separately for the two periods (1985-1996 and 1997-2014), and assumed only estimates from the second period were reliable. We additionally undertook one model run assuming the same survival for the whole study period, to be more confident in our assumptions. We also tested for a time variant survival for immature and adults. We estimated the probability of dying in fishing gears and we additionally tested an age effect on this probability, i.e. separately for immature and adults. After modeling first recapture probabilities and keeping the remaining parameters time varying (models not shown), we selected a model in which recapture probabilities were kept time-variant except for the last five years of the study, when fieldwork effort was rather constant. As we had no enough data to check if recovery probability varied over time, we kept it constant.

Once the probability of bycatch was estimated, we then estimated hypothetical survival without incidental capture, both for immature and adults. We did so by adding the estimated probability of dying in fishing gears to the survival probability.

Breeding success and fishing discards

Sant Carles de la Rapita harbour holds the bulk of the important trawling fleet operating off the Ebro Delta, where Balearic shearwaters often forage (Louzao *et al.* 2006). The amount of trawling discards and trawling landings are correlated (Oro & Ruiz 1997), thus we used the statistics of trawling landings at this harbour between March and June (i.e. encompassing most of the breeding cycle) as a proxy of inter-annual variability in food availability. Breeding success of monitored study nests was calculated between 1997-2004 and 2010-2013, as the percentage of fledglings by eggs laid each season. We then used generalized linear models (GLM), with a logit link function and binomial error, to test for the potential association between our proxy of food availability and the breeding success for the 12 year period. The intercept of this logistic regression function corresponded to the estimated breeding success in the absence of discards, and this value was used as the breeding success in the scenarios with discard banning.

POPULATION MODELLING

We formulated a seven stage-class matrix population model (Table S1 in Supporting Information, Fig. 1) to assess the population growth rate of Balearic shearwaters under current and possible future environmental conditions. The model followed a pre-breeding census format, and was based only on females; assuming equal survival between sexes and monogamy (Oro *et al.* 2004). All projection models were developed and executed in program R (http://cran.r-project.org).

Deterministic analysis

We first carried out a projection for the next 100 years on a deterministic model that included mean values of the estimated vital rates and yielded the deterministic population growth rate or λ (largest eigenvalue of the population matrix, Caswell (2001)). All the vital rates used in the model were derived from this study, except the probability of skipping breeding, which we obtained from Oro *et al.* (2004). To initialize the models we used the highest available estimate of current population size, obtained from at-sea censuses (Arcos *et al.* 2012; Arroyo *et al.* 2014). In addition to population growth rates, the deterministic model was used to estimate other important information, such as the stable age distribution, generation time, reproductive value and the sensitivities and elasticities.

Stochastic analysis

While the deterministic growth rate describes the population trend for constant, invariant vital rates, we also constructed a stochastic model to account for variability in those rates and hence the risk of population decline or extinction. To do so, we picked random values for survival and fertility rates from beta distributions in each year of simulations, using the mean and variance values from our field data and capture-recapture analysis. We did not consider density-dependence in our model because population growth rate was negative in all cases. Models were run using Montecarlo simulations for ‘100 years’ and ‘1000 population’ trajectories. We ran models under different scenarios considering the current fisheries impact, and hypothetical scenarios with different combinations of bycatch intensity and discard availability according to EU fishing policies (Table 1). We also set some scenarios using the lowest survival estimates from a range of published values for similar Procellariiforms of the *Puffinus* genus, which are less affected by bycatch and other anthropogenic mortalities (Table S2). In all scenarios, survival of non-breeders was considered to be equal to the survival of breeders, because we assumed that environmental stochasticity equally affected the two groups (Table 1). Under all scenarios we estimated the mean stochastic population growth rate (λ_s) over a short and relevant time horizon of 100 years from 1000 projections, together with 95% confidence intervals:

$$\lambda_s = \frac{1}{1000}\sum_{i=1}^{1000}\exp\left[\frac{\ln(N_i(T=100)) - \ln(N_i(T=0))}{100}\right]$$

Detecting overharvesting

We further evaluated the impact of longline bycatch as an additional source of mortality, using the “potential biological removal” PBR (Dillingham & Fletcher 2008). We first calculated the maximum potential annual growth rate (λ_{max}) by means of the “demographic invariant method” DIM (Niel & Lebreton 2005):

$$\lambda_{\max} \approx \frac{(s\alpha - s + \alpha + 1) + \sqrt{(s - s\alpha - \alpha - 1)^2 - 4s\alpha^2}}{2\alpha},$$

which assumes constant adult survival probability s and the average age at first reproduction α. Since s of Balearic shearwaters was affected by longline bycatch (see Results), we took the average minimum survival estimates from studies on closely related Procellariiforms not affected by additive mortality (0.917, see Table S2). To obtain α we first calculate α_i (the probability of a bird of age i to be a first-time breeder) from our recruitment probability r_i through the equation:

$$\alpha_i = r_i \prod_{y \le j < i}(1 - r_j), i \le f,$$

where y was the youngest age at breeding and f was the full age at recruitment. From α_i we obtained α as:

$$\alpha = \sum_i \alpha_i ,$$

which equalled 4.83 for Balearic shearwaters in our study.

Then we calculated PBR as:

$$PBR = \frac{1}{2} R_{\max} N_{\min} f$$

where $R_{\max}$ is the maximum annual recruitment rate, equalling ($\lambda_{\max}$ - 1), $N_{\min}$ is a conservative estimate of population size and f is a recovery factor with values ranging from 0.1 to 1 depending on population conservation status and the best adaptive management action to be taken.

To calculate $N_{\min}$, we took the 20$^{\text{th}}$ percentile of the distribution of population size following the equation (Dillingham & Fletcher 2008):

$$N_{\min} = \hat{N} \exp\left(-0.84\sqrt{\ln(1 + CV_N^2}\right),$$

where $\hat{N}$ equals 23,780 individuals, and CV_N equals 0.03, using mean and its 95% CI of that estimate provided by Arroyo *et al.* (2014). We set f at a conservative value of 0.1, typical for endangered species.

Results

During March-June of 1985-2014 a total of 1,344 individuals were captured and ringed at the study colony, corresponding to 761 chicks (57%) and 583 adults (43%). A total of 394 marked individuals were recaptured at least once, of which 179 were marked as chicks and recruited as breeders at the study colony (24% of all ringed chicks). More than half of the marked adults (54%) were never recaptured. We obtained 11 recoveries, five dead from bycatch and six from unknown causes.

Recruitment analysis

The GOF for the Cormack-Jolly-Seber model was poor (ĉ =3.993) mainly due to a transient effect from individuals ringed as chicks. Thus, we included age in our models and then corrected for the remaining overdispersion with a ĉ = 2.270.

Two models were best ranked in model selection: while one model suggested that there are four ages of recruitment (from 3 to 6), the other suggested that recruitment was completed at age 5 (Models 1 and 2 respectively, see Table 2). Estimates from the two models were very close, and showed that almost all individuals recruited at 6 years old, with low recruitment at 3 years of age. We took recruitment estimates from Model 2 because it had fewer parameters and was more conservative for assessing population viability. Probabilities of recruitment at age *i* (r_i; mean and 95% CI) from Model 2 were: r_3 = 0.037 (0.002-0.450), r_4 = 0.295 (0.100-0.611), r_5 = 0.726 (0.409-0.910), and r_6 = 1 (for 6 years old and older individuals). The model assuming equal survival for immature and non-breeding adults was not well supported (Model 5, Table 2).

Global analysis

When analysing the complete data set, the GOF for the Cormack-Jolly-Seber model was poor ($\hat{c}$ = 3.264) due to the presence of transients among individuals ringed as chicks. We included age in our models and corrected for remaining overdispersion with a $\hat{c}$ = 2.350.

The model with the lowest QAICc value (Model 1, Table 3) differentiated the two periods with and without recaptures: this model indicated that survival did not vary significantly over the years and it was much lower for 1 and 2 year old (immature) than for older birds: 0.436 (95% CI: 0.353-0.522) and 0.813 (95% CI: 0.787-0.837) respectively. Survival of non-breeders was not estimable given our data. The model considering the whole study period (1985-2014) had a higher QAICc value (Model 3, Table 3) and confirmed that the first period without recaptures was only valuable for using birds marked during this period. Given the limited data on bycatch events, we could not disentangle if there was a different bycatch probability for immature and adults, because both models had similar QAICc values (Models 1 and 2, Table 3). Incidental capture in longlines was estimated at 0.45 (95% CI: 0.124-0.841), which meant that approximately half of mortality was attributable to bycatch, with a probability of mortality from longlines of 0.084 and from other causes of 0.102. Local survival without incidental capture was thus estimated at 0.520 (SE: 0.044) and 0.898 (SE: 0.013) for immatures and adults, respectively.

Breeding success and fishing discards

Mean breeding success at the study colony was estimated at 0.665 (SE: 0.038), ranging from 0.400 to 0.920 fledglings per breeding pair. Breeding success was positively associated with trawling landings (z = 3.170, d.f. = 11, P = 0.001, Fig. S1). The intercept of the logistic regression function corresponding to the estimated breeding success in the absence of discards was 0.433 fledglings per pair (SE = 0.137).

POPULATION MODELLING

Deterministic analysis

The estimated deterministic λ was 0.863, reflecting an annual decline of about 14% in population size, and a generation time of 12.5 years. The stable stage distribution for the species showed that 60.8% of females are breeders (Table S3). Hence, taking into account the recent global population estimate, the number of breeding pairs would be ca. 7,600. We estimated a time to extinction of 63 years (95% CI: 61-65). Sensitivity and elasticity analysis showed that changes in survival of breeding adults, and to a smaller extent the probability of a skipping breeder to reproduce again, had the largest effect on the population growth rate (Table S3).

Stochastic analysis

When adding environmental stochasticity under current conditions, the mean growth rate for the population λ_s was 0.864 (95% CI: 0.824-0.894) (Table 1). The only scenarios with stable or increasing trends were those in which survival reached values comparable to those described for closely related Procellariiforms (scenarios 5 and 6, Table 1, Fig.2). With these higher survival probabilities, the population should avoid extinction even with a ban on discards reducing fertility (Scenario 5, Table 1).

Detecting overharvesting

Using the DIM approach, λ_{max} was 1.101 (range 1.087-1.112), i.e. that under ideal demographic conditions, the population cannot grow at a rate higher than 11.2% per year. A conservative estimate of population size N_{min} was calculated at 19,965 shearwaters, from which we estimated a PBR of 100 shearwaters dead at fishing gears each year (range 87-112).

Discussion

Fossil records of Balearic shearwaters suggest they had a very large population until the arrival of human colonizers to the Balearic archipelago ~$4{,}2\cdot10^3$ years ago, which brought alien carnivores and rodents that have decimated most of the breeding sites (Alcover, Seguí & Bover 1999). Harvesting was also a major pressure in historical times, though it is residual nowadays. New anthropogenic impacts appeared in recent decades, notably habitat loss by urbanization and bycatch in fisheries (Table S3)(Lewison *et al.* 2012). Oro *et al*. (2004) performed a PVA using demographic data from two predator-free sites and concluded that the population would reach extinction in a few decades. Ten years later, our results confirm this prediction, despite considering a larger base population. Our latest results should be considered as more robust, as they are based on a larger (and updated) dataset, and use improved, up-to-date capture-recapture modelling procedures. Moreover, they show that fisheries are a crucial factor for the viability of the species.

Under the present scenario we predicted a time to extinction of 63 years, which confirms that the Balearic shearwater is one of the most endangered bird species in the western Palaearctic (BirdLife International 2015). Two opposite biases may have occurred in our study. Firstly, survival and fecundity were probably overestimated, because these parameters are impacted in most colonies by alien predators (Arcos 2011), but were not present in the study colony. Secondly, our survival estimates were local, i.e. did not distinguish mortality from permanent dispersal. While this last bias was likely very small for adult survival (breeding dispersal in Procellariiforms is very low, e.g. Sanz-Aguilar *et al.* (2011)), it might be important for immature survival, since natal dispersal may not be negligible (Genovart *et al.* 2007). Overall, our prediction for the current scenario was rather conservative, indicating that urgent conservation action is necessary to halt the extinction of the Balearic shearwater.

Perturbation analysis confirmed that changes in fecundity and adult survival have the smallest and the greatest effect on population growth rate, respectively, as previously recorded for shearwaters (Yearsley, Fletcher & Hunter 2003). These analyses also showed that together recruitment and skipping breeding, have a high total elasticity

(~25% in total), indicating that the two are probably buffering mechanisms when environmental conditions are poor (increasing sabbatical rates) or when additive mortality occurs (increased recruitment of young birds)(Yearsley, Fletcher & Hunter 2003; Jenouvrier *et al.* 2005).

THE IMPACT OF FISHERIES

Incidental capture in fishing gears represents a major cause of additive mortality for many seabirds worldwide, and it has been the focus of conservation concern and research in the last three decades (Lewison *et al.* 2012). Observer on-board programmes for longline vessels in the Mediterranean have reported low rates of bycatch for Balearic shearwaters (Belda & Sanchez 2001; Laneri *et al.* 2010), although there is increasing evidence of regular mortality, particularly by demersal longlines (ICES 2013). Moreover, events of "mass" mortality, with over 100 birds per event, appear to occur with relative frequency, though they are difficult to detect through observer programmes with limited coverage (Besson 1973; Arcos, Louzao & Oro 2008; ICES 2008; Louzao *et al.* 2011). Bycatch impacts from other gears, such as trawlers and purse-seine vessels, have also been reported recently (Oliveira *et al.* 2015). Despite there is not a reliable estimate of the number of birds caught per year, there is no doubt that this figure is well over our estimate PBR value, and the estimated bycatch as a minimum of half of the mortality detected in Balearic shearwaters confirm that current fishery impact is unsustainable. Our bycatch estimate should be considered as conservative because some recovered marked birds on beaches were assigned as unknown cause of death, but were probably drowned after release from fishing gear entanglement (Generalitat Valenciana 2012). The only scenarios yielding positive population growth rates were those assuming survival rates of other *Puffinus* species with little or no anthropogenic mortality.

The imminent scenario arising from EU fishing policies poses both threats and opportunities for the Balearic shearwater, and careful management is recommended to minimise fisheries impacts on this endangered seabird. Seabird bycatch has been incorporated into the EU agenda, and efforts to reduce this source of mortality are expected (Table S3), although so far progress has been very slow (ICES 2013). Conversely, the so-called "discard ban" (Table S3), if ultimately beneficial for the marine ecosystem, could bring negative effects for the Balearic shearwater and other seabirds in the short term (Bicknell et al. 2013). First, it could accelerate the decline of the species by reducing breeding success. Second, attendance and bycatch risk of shearwaters at longliners and other fleets may increase when trawlers do not operate (Garcia-Barcelona *et al.* 2010; Laneri *et al.* 2010), so a discard ban might increase bycatch and accelerate extinction probabilities. On the long term, however, if the discard reduction is actually accompanied by efforts to increase selectivity and reduce fishing pressure, this should be regarded as a beneficial measure for the seabirds, as fish stocks (i.e. natural prey) are expected to recover.

CONCLUSIONS AND RECOMMENDATIONS

Survival estimates, as well as bycatch mortality estimated by capture-recapture modelling, suggest that the global population of Balearic shearwaters is not viable in the long term. While the impact of alien predators can, and should be, urgently addressed (Nogales *et al.* 2004), actions to stop or reduce bycatch are fraught with challenges because of the large spatial scales to be covered (Guilford *et al.* 2012; Louzao *et al.* 2012), the range of multi-national fishing fleets involved and socio-economic considerations. But reducing bycatch rates in the short term is an urgent conservation priority. More data are required to determine which factors increase bycatch rates and which are the critical areas with highest impact, and it is crucial to then apply measures such as time restrictions on fishing activity, bycatch mitigation technology and practices, as well as the education of stakeholders and consumers. Finally, it is essential to set up demographic long-term studies, to allow researchers to diagnose with reliability the effectiveness of all those actions and to apply an adaptive management process (Lahoz-Monfort, Guillera-Arroita & Hauser 2014). Although this would require long-term financial investment, these studies would also be relevant to a wide range of seabirds and marine predators, as well as the whole marine ecosystem.

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Data accessibility

Balearic shearwater data it is available at http://cedai.imedea.uib-csic.es/geonetwork/srv/es/main.home.

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Table 1. Estimates of demographic parameters used in population models (standard errors in brackets) for each scenario considered, together with its mean stochastic population growth rate λ_s and 95% confidence intervals. Scenario 1: current situation. Scenario 2: reduced breeding success under future ban of discards. Scenario 3: conditions under future ban of discards but bycatch reduced. Scenario 4: current situation and bycatch reduced. Scenario 5: hypothetical conditions with minimum survival probabilities described for closely related Procellariiforms in optimal environments, and with ban of discards. Scenario 6: Same demographic parameters than scenario 5 but no ban of discards. Sex ratio was set to 0.5 in all models. Recruitment and sabbatical estimates were common for all scenarios; recruitment was 1 for individuals >6 years old.

Scenario	1	2	3	4	5	6
Survival affected by bycatch	yes	yes	no	no	no	no
Discard banning	no	yes	yes	no	yes	no
Demographic parameter						
Adult survival	0.813 (0.013) *	0.813 (0.013) *	0.900 (0.013) *	0.900 (0.013) *	0.917 (0.014)	0.917 (0.014)
Immature survival (1-2 y)	0.436 (0.044) *	0.436 (0.044) *	0.520 (0.044) *	0.520 (0.044) *	0.853 (0.043)	0.853 (0.043)
Breeding success	0.665 (0.134)	0.433 (0.137)	0.433 (0.137)	0.665 (0.134)	0.433 (0.137)	0.665 (0.134)
Sabbatical probability			0.261 (0.063)			
Recruitment probability						

λ_s	0.861	0.845	0.939	0.959	1.003	1.042
λ_s lower 95% CI	0.829	0.818	0.904	0.923	0.950	0.987
λ_s upper 95% CI	0.892	0.873	0.970	0.993	1.058	1. 082

Table 2. Model selection for *recruitment analysis* (see Methods). Notation for recruitment indicated the different age groups considered: for instance, “3, 4, ≥5” showed different recruitment probabilities for 3, 4 years old and older birds. Np = number of identifiable parameters. w_i = Akaike weight, which represent the relative likelihood of model *i*.

Model	Survival	Recruitment	Np	Deviance	QAICc	ΔQAICc	w_i
1	Two age classes	3,4,5, ≥6	27	2704.913	1247.222	0	0.50
2	Two age classes	3,4, ≥5	26	2712.815	1248.633	1.41	0.25
3	Two age classes	3,4,5,6, ≥7	28	2704.834	1249.263	2.04	0.18
4	Two age classes	3, ≥4	25	2723.411	1251.234	4.01	0.07
5	Breeders/Non Breeders	3,4,5, ≥6	26	2728.911	1255.728	8.506	0.01
6	Two age classes	constant	24	2748.448	1260.203	12.98	0.00

Table 3. Model selection from the *global analysis* (see Methods) for estimating survival and the probability of dying in fishing gears, by age (immature and adults). Recruitment probability was fixed at values previously estimated. Given that no resights were carried out from 1985 to 1997, some models considered two separate periods: 1985-1996 and 1997-2014. Recapture probability was fixed to zero in years with no resights. We kept this probability variable in time except for the last five years of the study (2010-2014), when the recapture effort was highly constant among years.

Model	Survival	Bycatch	Recapture	Deviance	QAICc	ΔQAICc	w_i
1	Constant by age, two periods	Constant	1985-2009*t,2010-2014	4681.646	2055.837	0	0.63
2	Constant by age, two periods	By age	1985-2009*t,2010-2014	4679.362	2056.930	1.09	0.37
3	Constant by age, one period	Constant	1985-2009*t,2010-2014	4737.408	2073.347	17.51	0.00
4	Time varying, two periods	Constant	1985-2009*t,2010-2014	4608.289	2102.293	46.46	0.00

Fig. 1. Life cycle diagram used to project the Balearic shearwater population (pre-breeding census). Birds indicated age-stage classes: N1: individuals 1 year old, N2: 2 years old, $N3_{NB}$: 3 years old not recruited, $N4_{NB}$: 4 years old not recruited, $N5_{NB}$: 5 years old not recruited, N_B: breeders, N_{NB}: animals in sabbatical that had bred at least once. ϒ: sabbatical probability, $r_{3,4,5}$: recruitment probability (probability of breeding for the first time) at 3, 4 and 5 years old respectively; ρ: hatching sex ratio, S1: immature survival (first and second year of life); S2: adult survival for a non-breeder; S3: adult survival for a breeder; f: fertility (fledging/female*year).

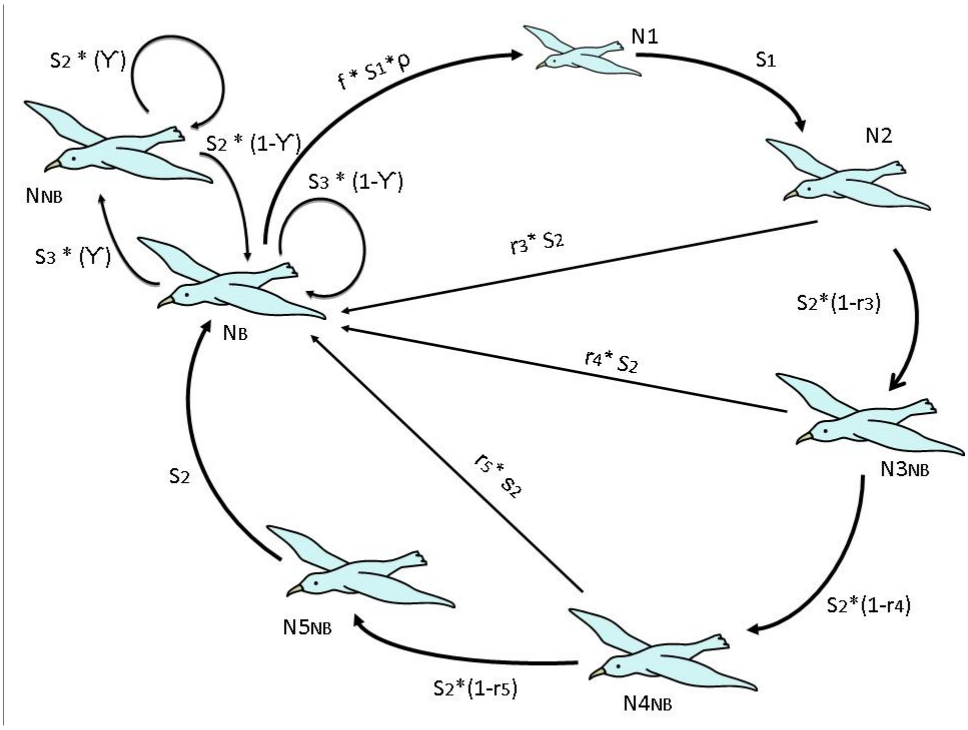

Fig. 2. Stochastic projections of Balearic shearwater population over 100 years under different scenarios proposed 1) current situation, 2) reduced breeding success under future ban of discards, 3) conditions under future ban of discards but bycatch reduced, 4) current situation and bycatch reduced, 5) hypothetical conditions with optimal survival probabilities and discard banning, 6) current conditions but with optimal survival probabilities. Each graph shows 20 randomly chosen trajectories from the 1000 population trajectories run in our Monte Carlo simulations.