Long-term reproductive impairment in a seabird after the *Prestige* oil spill

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Large oil spills are dramatic perturbations on marine ecosystems, and seabirds are one of the worst affected organisms in such events. It has been argued that oil spills may have important long-term consequences on marine organisms, but supporting evidence remains scarce. The European shag (*Phalacrocorax aristotelis*) was strongly impacted at population level by the *Prestige* oil spill, the biggest spillage in the eastern North Atlantic. In this paper, we report on the long-term consequences on reproduction of this coastal seabird, using temporal and spatial replicated data (before–after–control–impact design). Our study revealed long-term reproductive impairment during at least the first 10 years since the *Prestige* oil spill. Annual reproductive success did not differ before the impact, but after the impact it was reduced by 45% in oiled colonies compared with unoiled ones. This is a rare documentation of long-term effects after a major oil spill, highlighting the need for long-term monitoring in order to assess the real impact of this type of disturbance on marine organisms.

1. Introduction

Large oil spills are one of the most dramatic examples of large-scale pulse perturbations, but impact assessment has proved a difficult task [1]. Seabirds are one of the worst affected organisms in such events, and substantial numbers of seabird carcasses have been recorded immediately and in the subsequent months following major oil spills around the globe [2,3]. Prior to the *Exxon Valdez* oil spill, it was thought that impacts to seabirds derived exclusively from acute mortality [4], with no apparent effects at population level [5]. Research after this spill has challenged this traditional view, suggesting that the effect of oil spills may be complex and long-lasting due to, *inter alia*, ecosystem-driven effects [6]. Unfortunately, the lack of long-term seabird population data, both pre- and post-spill, has precluded robust assessment of the long-term effects of major oil spills on seabird populations [7,8]. Population parameters of seabirds show spatial and temporal fluctuations, the effects of which may be difficult to disentangle without long-term monitoring [8].

On 13 November 2002, the hull of the *Prestige* oil tanker wrecked and about 63 000 tonnes of heavy oil were released into the marine environment. Residual oil was still being detected nine years following the spill [9], and trophic changes in marine food web due to the presence of oil in the affected area have been documented [10,11]. Here, we examine the effect of the *Prestige* oil spill on the reproductive success of the European shag (*Phalacrocorax aristotelis*) during the first 10 years after the wreck. This coastal seabird was strongly affected by initial spillage [9,12,13]. Five years after the *Prestige* oil spill, the shag population breeding at oiled colonies was 70% lower than pre-spill counts [14]. The existence of pre-spill long-term reproductive monitoring of European shags at oiled and unoiled colonies allowed the use of temporal and spatial replicated design (before–after–control–impact (BACI) design; [15]) to distinguish between effects of the spillage event and natural temporal and spatial variation.
2. Material and methods

The study was carried out from 1994 to 2012 in the northwest of the Iberian Peninsula (electronic supplementary material, figure S1). Colonies in the most heavily oiled area were considered as ‘oiled’, and colonies outside this area were considered as ‘unoiled’ (see the electronic supplementary material, figure S1). Annual reproductive success was monitored in the study areas (see the electronic supplementary material). In order to study the potential effects of climatic variability on reproductive success, we used the North Atlantic Oscillation (NAO) and the Sea Surface Temperature (SST) indexes (see the electronic supplementary material).

Annual reproductive success was analysed by a linear mixed model, including area (oiled and unoiled; electronic supplementary material, figure S1), period (before and after the Prestige oil spill), NAO and SST as fixed effects. Year, nested within period and colony, nested within area, were included as random effects. In two colonies, the presence of invasive American mink (Neovison vison) was detected in certain years (2009–2012 at Illas Cies and 2012 at Castrios-Represas). In order to ensure that the results were not affected by the presence of this exotic predator, we included this factor in the model, and we also re-ran the same model while excluding reproductive events with predator presence.

The influence of environmental effects on a BACI analysis was tested by the interaction between period (before–after factor) and area (control–impact factor, see the electronic supplementary material). The statistical significance of the difference in reproductive success between pair comparisons (e.g. before–after, control–impact) was estimated by means of Monte Carlo randomization analysis (10 000 simulations without replacement; see the electronic supplementary material). We also tested any possible effect of recovery by restricting our analysis of postspill data, including the number of years after the Prestige oil spill in the model. Data are expressed as mean ± s.e.

3. Results

The annual reproductive success in the study area (figure 1a) was strongly affected by the interaction between area (oiled versus unoiled) and period (pre and post oil spill) ($F_{1,77.9} = 17.49, p < 0.0001$). Prior to the oil spill, reproductive success was similar in both areas (unoiled: 1.22 ± 0.16; oiled: 1.41 ± 0.20; randomization test, $p = 0.69$; figure 1b). By contrast, after the spill, the reproductive success was reduced by 45% in oiled colonies (0.87 ± 0.13) relative to unoiled ones (1.48 ± 0.20; randomization test, $p < 0.0001$; figure 1c). Indeed, in the oiled area the number of chicks fledged per pair was reduced by 40% after the spill (randomization test, $p = 0.0019$; figure 1d). In the model, year explained 16% of variance in reproductive success (year random term, $LRT = 4.4, p = 0.036$), indicating that reproductive success was annually correlated among colonies.

Annual variation in reproductive success was not explained by climate (NAO: $F_{1,70.3} = 1.11, p = 0.30$; SST: $F_{1,70.3} = 0.26, p = 0.61$). The presence of the American mink

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**Figure 1.** Trends in the reproductive success of the European shag. (a) Annual reproductive success (i.e. the number of fully grown chicks per nest, see the electronic supplementary material) from oiled (black circles) and unoiled (white circles) areas before and after the Prestige oil spill (mean ± s.e.). Dotted lines are used to join gaps without information. (b–d) Distribution of Monte Carlo simulations ($n = 10 000$) of the t-statistic values for the original data (see the arrows) and the t-statistic values for randomly allocated observations; (b) Prespill unoiled–oiled: $t = −0.49, p = 0.69$; (c) Postspill unoiled–oiled: $t = 5.38, p < 0.0001$; (d) Oiled before–after: $t = 2.83, p = 0.0019$. p-values were calculated as the probability of randomized t-test values exceeding the distribution of t-test values based on original data.
in the colonies reduced reproductive success, but this difference was not significant \((F_{1,91.2} = 3.84, p = 0.053)\). The interaction between area and period remained significant when the analysis was restricted to predator-free breeding events \((F_{1.79.2} = 23.84, p < 0.0001)\).

Climate variables tested did not significantly differ between pre- and postspill monitored years (oiled area SST: \(t_{13} = 0.79, p = 0.44\); unoiled area SST: \(t_{13} = 0.71, p = 0.49\); NAO: \(t_{17} = 1.02, p = 0.32\)). In the oiled colonies, time (years) after the Prestige did not influence reproductive success (figure 1a; \(F_{1,20.4} = 0.25, p = 0.63\)).

4. Discussion

The comparison of baseline data in oiled and unoiled areas suggests that the Prestige oil spill had a significant effect on the breeding performance of European shags. In these areas, annual reproductive success of European shags did not differ before the impact, but it showed marked differences after the spill, due to impaired reproduction in oiled colonies.

In our study area, parallel temporal fluctuations in reproductive success in both areas occurred prior and following the spill (figure 1), but climate fluctuations did not explain this pattern. Additionally, we found no indication of adverse environmental conditions for breeding shags after the Prestige oil spill. Indeed, climate (NAO and SST) was similar before and after the spill. In 2009, invasive American mink were detected for the first time in shag breeding areas on Illas Cies, an oiled colony, and in Castros-Represas, an unoiled colony. Although not significant, the presence of this predator reduced reproductive success, but the effect of the spill remained even when predator-breeding events were removed from the analyses. As far as we know, this is the only environmental factor that has changed since the oil spill.

Oil spills are unplanned events, and data deficiency on the natural variation of populations normally constrains the assessment of these events on affected populations [8]. An ideal expanded-BACI design should include temporal and spatial replication of data [15]. In the post-spill period, our dataset included a well-replicated design, several colonies (more than 6) in oiled and unoiled areas monitored over a long period (more than 8 years), and our analyses indicate strong differences in reproductive productivity between oiled and unoiled colonies. The data available from pre-spill years suggest that the annual reproductive success did not differ among colonies before the impact. In the oiled area, a single colony (Illas Cies) was monitored during the pre-spill period; this was, however, the largest colony in the oiled area (56% of population [14]). In this colony, annual reproductive success was higher in all pre-spill breeding seasons (7 years) compared with postspill data (8 years). Thus, temporal comparison strongly suggests a reproductive decline after the spillage.

In this study, we did not evaluate the causes underlying the reduction of reproductive success in oiled colonies, but seabird populations may have suffered from the sub-lethal effects of oil exposure and reduced food availability after the Prestige oil spill [10]. Previous studies have revealed the persistence of residual oil in the ecosystem even nine years after the accident [9] and the chronic exposure of marine organisms [16–18]. Long-term monitoring of de-oiled African penguins (Spheniscus demersus) after two major oil spills revealed reduced reproduction in those parents previously exposed to oil [19,20]. A variety of evidence indicated that European shags showed a dietary shift after the Prestige oil spill [10], which continued several years after the accident [21].

The European shag was the marine organism that showed the clearest impact of the Prestige oil spill at population level [17] and affected colonies did not show signs of recovery five years after the accident [14,21]. Our study revealed long-term reproductive impairment over at least the first 10 years after the spill. This study is a rare example documenting the long-lasting effects of a major oil spill on marine organisms, highlighting the need for long-term monitoring to evaluate environmental perturbations.

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Data accessibility. The data are provided in the electronic supplementary material and in dryad digital repository: http://dx.doi.org/10.5061/dryad.nd764.

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References


