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Mass mortality of seabirds in the aftermath of the *Prestige* oil spill

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Abstract. In the winter of 2002–03 the *Prestige* tanker spilled 60,000 tons of oil over the northern half of the Iberian Coastal Large Marine Ecosystem (northern Portugal to France). Most (c. 85%) of the 22,981 oiled seabirds reported were alcids (i.e., auks): Common Murres (*Uria aalge*), Razorbills (*Alca torda*) and Atlantic Puffins (*Fratercula arctica*). Here we estimated the mortality of alcids in Galicia (northwestern Spain), the area that received most of the *Prestige* oil and where half of the oiled seabirds were collected. We performed three experiments that included: (1) a test of several drift block models in open sea, to select the one that best fitted the drift of alcid carcasses; (2) the release of 450 drift blocks at 9 offshore points to assess the recovery rate of oiled alcids and its spatial variation; (3) the assessment of beach survey effort and the detectability of drift blocks. Mean mortality estimates and their bootstrapped confidence intervals were obtained through an estimation model that established: (1) a temporal limit of 23 days to block drifting; (2) spatial differences in the recovery rates of blocks depending on how far away from the coast they were released; (3) a correction factor accounting for detectability, and (4) the distribution pattern of the three alcid species involved according to three distance classes, based on ship surveys. The *Prestige* oil spill, in terms of acute seabird mortality, was one of the worst oil spills ever reported worldwide. Compared to other major oil spills the estimated mortality for the *Prestige* oil spill was higher than expected from the number of carcasses retrieved. We recommend that drift block assessments of seabird mortality should be included in contingency response plans to oil pollution emergencies; therefore, a supply of drift-blocks designed to mimic the drifting behavior of the marine bird species of interests should be at hand.

Key words: *Alca torda*; Alcidae; auk; drift experiment; *Fratercula arctica*; Galicia; Iberian Coastal Large Marine Ecosystem; oil spill; pulse perturbation; seabird; *Uria aalge*.

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Introduction

Large oil spills are dramatic examples of large-scale perturbation pulses in marine ecosystems as they increase exposure to toxic compounds in marine organisms over a wide area (Salomone

2002). In common with other pulse perturbations, large oil spills often result in rapid alterations of the density of one or more members of the communities affected (see Bender et al. 1984). This appears to be particularly true in the case of seabirds. Of all impacts on wildlife, the oiling of seabirds probably attracts the greatest public and scientific concern (e.g., Dunnet 1982, Wiens et al. 1984, Salomone 2002). Due to their high vulnerability and exposure, marine birds are amongst the most conspicuous victims of oil spills at sea and they are considered as suitable bioindicators of marine oil pollution (Furness and Monaghan 1987, Pérez et al. 2008, Munilla and Velando 2010, Velando et al. 2010). Substantial seabird losses have been often recorded in the aftermath of oil spills worldwide (Piatt et al. 1990, Burger 1993, Balseiro et al. 2005). In general, seabirds are particularly prone to marine oil pollution exposure because they spend much of their lives at sea, and their populations are patchily distributed and concentrate in coastal and offshore habitats, which often receive a build-up of oil (Irons et al. 2000, Wiese and Robertson 2004). Except in obvious circumstances, such as a spill close to a breeding colony, quantifying the impact of major oil spills on seabird populations has proved a difficult task. The impacts of oil spills commonly extend over wide spatial scales and may combine with environmental factors to cause fluctuations in seabird populations (Votier et al. 2005, 2008).

Records of seabird mortality during oil spill crisis usually come from beached bird surveys aimed at mitigating the impact of oil pollution upon seabird populations by eventually taking injured birds to rehab centers. The number of beached birds recorded in the aftermath of an oil spill is however, an unknown and small fraction of the total kill (Ford et al. 1987, Piatt and Ford 1996, Wiese and Robertson 2004). One experimental approach to enhance estimates of acute seabird mortality following oil spills is through drift experiments. Typically, a number of tagged wooden blocks or marked seabird carcasses are released into the sea (Burger 1993, Wiese and Jones 2001). Main sources of variation in drift experiments and seabird mortality records relate to oceanographic and environmental conditions, searching effort and the identity, distribution and abundance of the seabird species at risk. Thus, estimates of acute seabird mortality in the aftermath of an oil spill based on drift experiments must take into account several sources of uncertainty (Fig. 1). Furthermore, when wooden blocks are used, it is crucial that they mimic the drifting behavior of the seabird species at risk (Wiese 2003). Compared to drift blocks, seabird carcasses will sink in a rather short time and tend to be scavenged (Wiese 2003).

In the winter of 2002–03, the *Prestige* tanker spread about 60,000 tons of oil over a wide marine area lying from northern Portugal to France. In common with many other oil spills that occurred in middle and high latitudes of the northern hemisphere, a few alcid species (i.e., auks) comprised the majority (c. 85%) of the 22,981 oiled seabirds that were reported in beach surveys (García et al. 2003, Velando et al. 2005). In the present study, we aimed at estimating the mortality of alcids in Galicia (northwestern Iberia), the area that received most of the *Prestige* oil and where half of the beached oiled seabirds were collected. With the notable exception of Aquitaine, France, some 2000 km east to the sinking point (Castege et al. 2007), so far the estimates concerning the short-term seabird mortality due to the *Prestige* oil spill have little factual basis as they are mere extrapolations from drift experiments conducted elsewhere. We performed three different experiments during the period of highest seabird mortality, including: (1) a drift block experiment intended to select the drift block model that best approximated the drifting of alcid carcasses in natural conditions; (2) a sea cast drift experiment to assess the recovery rates of blocks and its spatial variation; and, (3) a beach cast experiment to estimate beach survey effort and differences in reporting rate between drift blocks and alcid carcasses. Additionally, we incorporated data on the distribution pattern of the alcid species that were mostly affected by the spill, based on ship surveys conducted off Galicia between January 2005 and November 2006. Our ultimate aim is to produce a sound estimation of seabird mortality caused by the *Prestige* oil spill and to offer our best practice advice in "in situ" estimations of seabird losses due to such large-scale pulse perturbations.

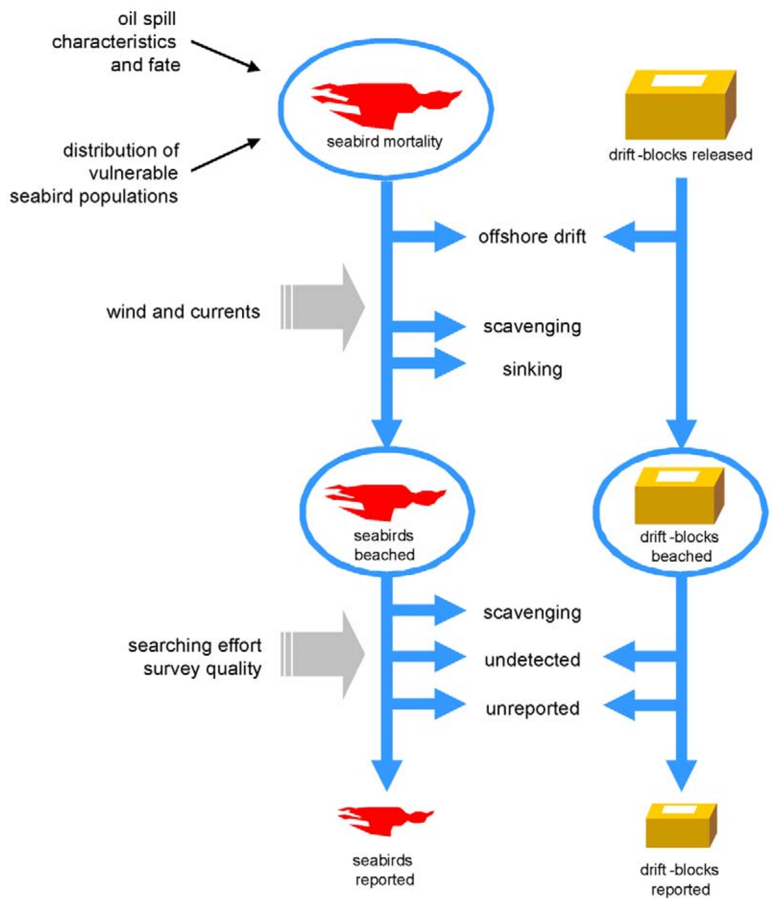

Fig. 1. Diagram showing the main sources of variation in drift experiments aimed at estimating seabird mortality at sea from oil spills. While actual seabird mortality depends on oil spill characteristics and the distribution of vulnerable seabird populations, the number of seabirds reported oiled depends on oceanographical conditions and searching effort at beaches. Drift blocks released at sea in the aftermath of the spill are intended to mimic the drifting behavior of impaired oiled seabirds and seabird carcasses; however, drift blocks do not sink and are not preyed by marine or terrestrial scavengers. In addition, drift blocks and beach washed seabirds are likely to differ in their detectability and reporting probabilities.

Methods

The oil spill

On November 13, 2002 a Bahamas-flagged, single-hulled tanker named Prestige, with 77,000 tons of heavy fuel sent an SOS alert 15 nautical miles off Cape Touriñana, Galicia (southeast North Atlantic; Fig. 2). After following an erratic course, to the north and then southwards, the tanker finally split in half and sunk at 42°15′ N and 12°08′ W about 260 km west of Vigo in the southwestern flank of the Galicia Bank (Fig. 2). The oil lost to the sea contaminated a vast coastal area that extended from northern Portugal to France (Fig. 2). At least three massive oil pollution pulses consisting of over 60,000 tons of oil reached the coasts of Galicia (see Montero et al. 2003). The first spill took place from 13 November until the ship collapsed six days later and first reached the coast on the morning of 16 November. The second (main) spill occurred at the moment the ship broke up and hit the coast on 1 December. The last spill included the oil that leaked through the breaches of the hull from the sunken tanker and washed ashore since 3 January.

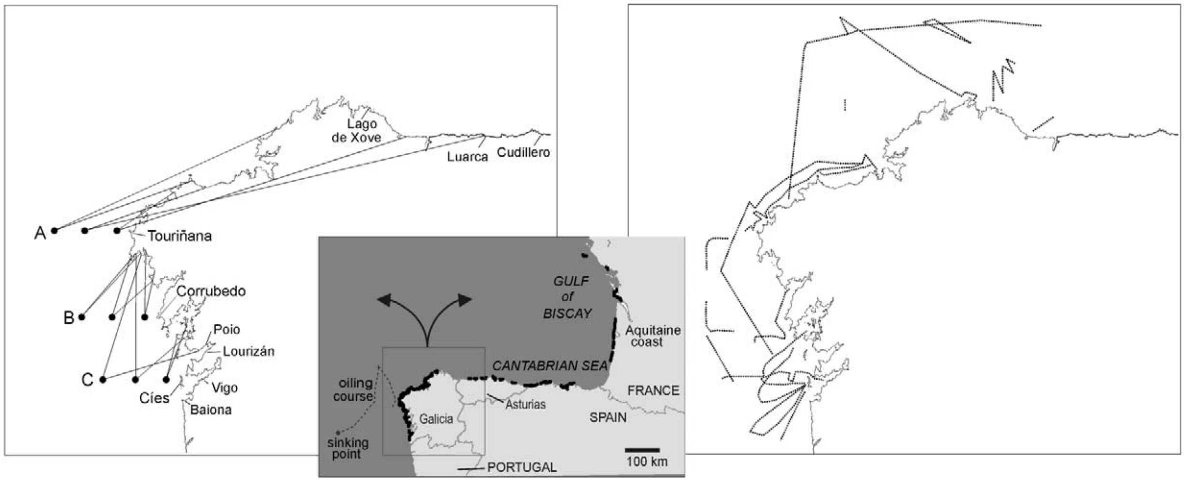

Fig. 2. Study area showing the coastal stretches where the oil beached, the course of the oil spillage (dashed line) and the sinking point of the *Prestige* tanker. The left enlarged area shows the nine points where the drift blocks were released at sea off Galicia. These were grouped along three latitudinal transects (A: Touriñana, B: Corrubedo, C: Cíes) and distributed at 5, 15 and 25 km intervals. For each of the release points, the two reporting locations that were farthest apart are shown. The right panel shows the routes (dashed lines) along which the seabird counts were located.

Beached bird survey data

A total of 12,023 seabirds, waterbirds and waders were recovered from beaches in Galicia through a beached bird survey scheme in which hundreds of trained volunteers intensively and extensively searched the oiled littoral (data provided by Dirección Xeral de Conservación da Natureza, Xunta de Galicia). The beach survey program was set up three days after the beginning of the spill (16 November 2002) and lasted until 31 August 2003. Up to 31 March (day 138, see Fig. 3), the beaches were searched daily and after that date the surveys were mainly conducted during weekends (see García et al. 2003). Over 95% of the oiled birds were reported between 16 November 2002 and 5 March 2003 (day 112, Fig. 3). The majority of the birds reported (9826, 81.7%) were alcids (i.e., auks), including Common Murres, *Uria aalge* (4492, 37.4%); Razorbills, *Alca torda* (2861, 23.8%); and Atlantic Puffins, *Fratercula arctica* (2473, 20.6%). Beached seabirds in Galicia mounted to 52.3% of the total number of beached seabirds reported in the area contaminated by the Prestige oil spill. In the rest of the oiled littoral alcids comprised a similar or even larger proportion of the seabird death toll (Portugal = 81.2%; Cantabrian coast = 91.2%; France = 83.5%). Beached birds still alive (20.6% of Murres, 25.4% of Razorbills and 6.8% of Puffins) were swiftly taken to rehab centers but only a handful survived and were released (all aquatic birds = 301, 2.46%; alcids = 178, 1.81%). Considering that their survival probability is likely to be very low (Balseiro et al. 2005, Mead 1997) we assume that all birds reported beached, whether dead or alive, were killed at sea by oil.

Drift block design

The design of our drift blocks followed Wiese and Jones (2001), i.e., wooden blocks with a steel plate ballast to adjust buoyancy and area exposed to the wind so to mimic alcid carcass drift. Of the three alcid species involved, Common Murres and Razorbills are almost equal in size whereas Atlantic Puffins are about 30% smaller. We assume that at the time of the spill (mid-November) first-year birds were about the same size as adults. Six drift block models, with equal density (approximately 0.85 g/cm^3) differing in dimensions, were tested in open sea against free drifting Common Murre and Atlantic Puffin carcasses. The test was conducted at Baiona Bay. The drift of blocks and carcasses was monitored for four hours and the models keeping closer to the bird corpses were considered the

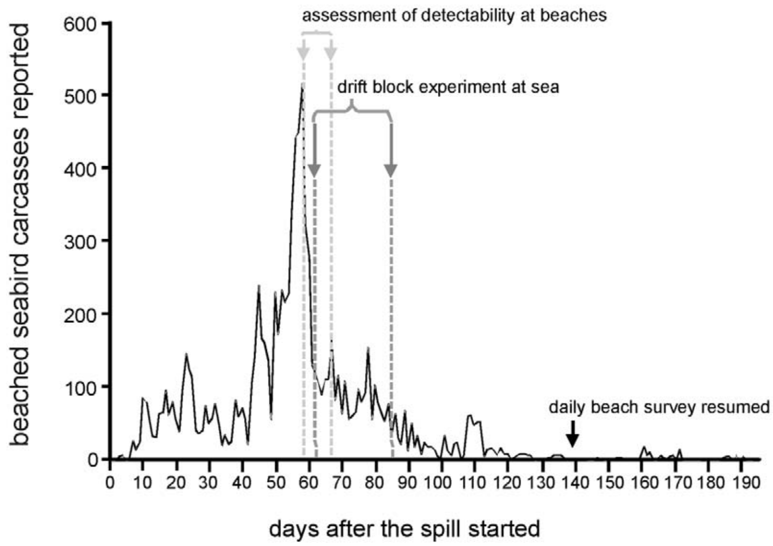

Fig. 3. Daily changes in the number of beached seabirds retrieved from the coast of Galicia in the aftermath of the *Prestige* oil spill and timing of the experiments used to estimate seabird mortality. Beaches were searched on a daily basis from the beginning of the spill to the end of March.

most appropriate. The two models selected were: the 14.5 × 9 × 9 cm wooden block with a ballast weight of 397 g (hereafter the "murre" type) for Common Murres and Razorbills (similar to Wiese and Jones 2001); and the 9 × 9 × 9 cm and 248 g ballast weight for Atlantic Puffins. Blocks were provided with an identification tag specifying reporting contact information that consisted of two phone numbers and a "please report" message.

Sea cast drift block experiment

In total, 437 drift blocks (216 "murres" and 221 "puffins") were released from a helicopter on 14–15 January 2003 (62 days after the spill started; see Fig. 3). Release points were spaced 5, 15 and 25 km along three longitudinal westward transects (Touriñana, Corrubedo and Cíes), thus covering the continental shelf of central-south Galicia (Fig. 2). The recovery rate R was defined as the proportion of blocks recovered; thus, $R =$ blocks recovered/blocks released. Unlike wooden blocks, seabird carcasses cannot drift forever, as they will eventually rot and sink. Experimental approaches to estimate the length of time that alcid carcasses remain afloat have come to different results, ranging from 30 days indoors (Castege et al. 2007) to 10–14 days in more natural conditions (Wiese 2003). To calculate the recovery rate we set a time limit of 23 days after release, equivalent to the midpoint between those two experimental estimates of carcass persistence while allowing for a reporting delay of 2 days (see Results). Therefore, the blocks recovered after 6 February (four blocks) were excluded from the calculation of recovery rates.

Drifting velocity and direction of floating objects is mainly determined by wind and currents. Flint and Fowler (1998) showed that drift block recovery changed dramatically depending on wind direction (offshore vs. inshore). To assess whether weather conditions during the drift experiment were representative of those prevailing during the whole spill period, we compared wind speed and wind direction between the experimental period (14 January–6 February; see Fig. 3) and the beached bird survey period when over 95% of the total number of oiled birds were reported (16 November–5 March). These variables were recorded daily at the weather station of Lourizán, located to the south of the oiled area (Fig. 2) (⟨http://meteogalicia.es/galego/observacion/estacions/estacions.asp?idEst=10047&idprov=1⟩).

Detectability experiment at beaches

Estimates of avian mortality rates using drift blocks can be highly misleading if beached blocks and beached seabird carcasses do not have similar reporting probabilities. All other factors being equal, beached seabirds are subject to scavenging (Ford 2006, Van Pelt and Piatt 1995). Moreover, other biases can arise regarding differences in detectability. To account for potential differences in the reporting rate of beached blocks and birds we performed an experiment to estimate the probability of detection of drift blocks relative to alcid carcasses. Between 10 and 18 January 2003, during the period when beaches were searched daily (Fig. 3), 49 blocks (25 "murres" and 24 "puffins") and 44 ringed alcid carcasses were released on 50 sandy beaches selected at random in Galicia. Relative detection B was defined as $B = c/b$, where b is blocks recovered/blocks released at beaches, and c is carcasses recovered/carcasses released at beaches.

Distribution pattern of alcids at sea

Information on the distribution pattern of wintering Common Murres, Razorbills and Atlantic Puffins in Galicia was based on ship surveys. These were conducted by a SEO/BirdLife observer in January–March 2005 and November 2005–February 2006 aboard a research vessel of the Spanish Institute of Oceanography and commercial fishing boats, using standardized strip-transect techniques (Tasker et al. 1984). The transects were conducted along the routes followed by the ships (Fig. 2) and were not designed as a statistical survey. A 300-m strip-width transect band was used and birds were summed up into 10-minute survey bins. In total, 233 10-minute bins were conducted, covering a distance of 69.9 km and a survey area of 222.8 km^2. All observations of alcids, whether sitting on the water or in flight and both within and outside the transect strip were considered here and no corrections were made for detectability. Alcids were observed on 91 (39%) transects and totaled 236 birds of which 190 were identified to species: 11 Common Murres, 36 Razorbills and 143 Atlantic Puffins (1, 6 and 2 respectively outside transects). The geographical coordinates of the midpoints of the transects were used to calculate individual distances to the nearest coast on Google Earth (distance tool). Data were grouped into three distance classes ($<$10 km, 10–20 km and $>$20 km) in accordance to the location of the release points for drift blocks (5 km, 10 km and 25 km, respectively).

Estimate of acute seabird mortality due to the Prestige oil spill

Oiled seabirds found alive or dead on the coast represent only a fraction of the overall short-term mortality (Burger 1993); thus, the actual mortality (N) may be estimated as the number of victims reported from beached bird surveys (M) corrected by a certain recovery rate (R); i.e., $N = M \times R$.

The marine area affected by an oil spill can be divided into k strata, each with a different recovery rate for drifting oiled seabirds Ri. We modeled a stratified population of unknown size of j seabird species, so that Pij is the proportion of birds of the jth species in the ith strata. If we assume that the risk of oiling for seabirds at sea is the same for all strata, then, for k strata and m species, the actual mortality (N) is estimated as follows:

$$N = \sum_{j=1}^{m} \sum_{i=1}^{k} (M \times Pij)/(B \times Ri)$$

where B is the detection factor for the beached bird survey program initiated in response to the oil spill (assuming a similar detectability for beached seabirds along the coast surveyed; see Results).

In our particular case, we defined strata by distance from shore ($k = 3$), in accordance with our analysis on block recovery (see Results). The relative abundances by stratum of the three species considered (Razorbill, Common Murre and Atlantic Puffin; $m = 3$) was estimated from the ship counts, whereas the detectability factor (B) was estimated from the beach experiment.

The assumption of a homogenous risk of oiling for seabirds in the study area may be applicable here. Though the tanker started leaking oil very close to shore, it was forced to move away into the open sea first to the north and then southwards (Fig. 2). Most of the oil was lost beyond the limit of the continental platform where it generated an oil front that swept the marine area where alcids winter on its way to the coast.

Review of drift experiments and estimates of seabird mortality

In order to compare the results of our study both in terms of the recovery rates of drift blocks and the number of seabirds killed, we conducted a search of the scientific literature (Google Scholar database) on drift-block and carcass drift experiments updating those made by Piatt and Ford 1996 and Wiese and Jones 2001. Additionally, estimates of acute seabird mortality from other marine oil spills was collated via the CEDRE (⟨www.cedre.fr⟩) and IncidentNews (⟨www.incidentnews.gov⟩) website databases, which summarize information on marine spills worldwide since 1947. When specific quantitative information on seabird mortality was not available from these sources, the search was further refined by introducing the name of the vessel and the word "seabird" as keywords.

A direct comparison with mortality figures reported from other oil spills is problematic due to methodological issues and to the fact that many estimates are mere extrapolations of "standard" recovery rates. As a way to compare our mortality estimate with such extrapolations, the results reported by the drift experiments were used to calculate an average recovery for all experiments ($n = 35$) and for the subset of experiments aimed at alcids ($n = 19$). A sounder comparison between our results and the mortality figures reported from other oil spills was restricted to the accidents where seabird mortality was assessed by means of drift experiments ($n = 8$). Thus, we fitted a regression line between the mortality estimates and the number of beached seabirds reported.

Statistical analyses

To compare wind conditions between the experimental period and the beached bird survey period when over 95% of the total number of oiled birds were reported, we performed an ANOVA with wind speed log transformed (to ensure normality; K-S test = 0.078, df = 110, P = 0.097) as dependent variable and period as factor. Wind direction was compared between periods using a non-parametric Watson's test for circular distributions.

The effect of the type of block ("murre" vs. "puffin") and the location of release points (latitude and distance to the coast) on block recovery rates were analyzed using a Generalized Linear Model with binomial error and logit link. In the beach experiment, differences in detectability between blocks and carcasses were analyzed by means of a 2×2 contingency table.

Lastly, to estimate confidence limits for the mortality calculated by our model we performed a bootstrap resampling (Efron and Tibshirani 1993, Lunneborg 2000) using PopTools (Hood 2010). The results of the sea cast drift block experiment and the detectability experiment at beaches were resampled 10,000 times to derive bootstrap confidence intervals (hereafter CI) on the number of blocks or carcasses recovered as 2.5% and 97.5% bootstrapped percentiles. The same routine was used to estimate confidence intervals for the set of recovery rates obtained from the literature review.

Results

Sea cast drift block experiment

Wind speed and direction during the experimental period did not differ from values measured during the rest of the spill period ($F_{1, 109} = 0.010$, $P = 0.920$; $U^2_{4,6} = 14.31$, $P > 0.10$ respectively). In total, 74 of the 437 blocks released in Galicia were recovered ($R = 0.169$; CI: 0.135–0.204) though in two blocks the code number in the tag was unreadable. Blocks were reported over a wide area, from Poio to Luarca (Fig. 2), with only one of the blocks recovered outside Galicia (Luarca, Asturias). Blocks tended to drift to the northeast and no blocks were reported to the south of their respective release points (Fig. 2). Assuming that they followed the shortest possible marine route, the median and mean distance traveled by blocks was 45.4 km and 70.4 km ($n = 72$; range = 27.0–271.3 km).

Recovery rates of "murre" and "puffin" blocks were not statistically different ($\chi^2 = 0.09$; $P = 0.768$) and consequently the two block types were pooled together for calculations. Blocks were reported from 19 January (4 days after release) to 23 February (40 days after release). Median and mean recovery times were respectively 11.7 and 10.0 days ($n = 73$; range = 4–40 days; one case of delayed reporting, 167 days after release, was not included in this calculation). Based on these, drift velocity was estimated as 6.5 km day^{-1} (range = 1–18). Recovery rates by

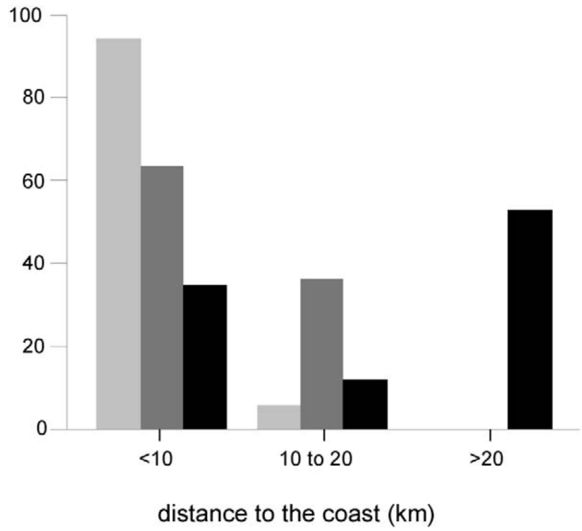

Fig. 4. Alcid distribution off Galicia. Spatial distribution of alcids with respect to distance to the coast. Based on 190 observations at ship-based counts. Light grey bars: Razorbill; Deep grey bars: Common Murre; Solid bars: Atlantic Puffin.

point of release ranged from 0.040 to 0.408. Distance to the coast had a significant effect upon recovery rates ($\chi^2 = 5.30$; $P = 0.021$) whereas latitude (transect) did not ($\chi^2 = 0.62$; $P = 0.430$); accordingly, instead of using a recovery rate for each of the nine release points we used a different recovery rate for each of the three distance classes considered in our design (i.e., 5, 10 and 25 km offshore) as follows: $R_5 = 33/149 = 0.221$, CI: 0.154–0.289; $R_{15} = 16/148 = 0.108$, CI: 0.061–0.162; $R_{25} = 19/140 = 0.136$, CI: 0.086–0.193.

Detectability experiment at beaches

Blocks were detected in a significantly higher proportion than birds ($\chi^2 = 4.56$, df = 1, $P < 0.05$). The recovery rate of blocks at beaches was 34/49 = 0.694 (CI: 0.551–0.816) and the corresponding recovery rate of carcasses was 20/44 = 0.455 (CI: 0.318–0.591). The correction factor accounting for differences in detectability was then estimated as $B = 0.655$ (CI: 0.431–0.928). Interestingly, there was delay of 2.1 ± 4.5 days (median = 1 day; n = 34) between release and reporting times (no data for carcasses).

Distribution pattern of alcids at sea

Data from ship surveys suggested wide differences in the winter at-sea distribution pattern of the three alcid species off Galicia with respect to distance to the coast (Kruskal-Wallis test; ($\chi^2_2 = 9.216$, $P < 0.05$). Fig. 4 shows the proportion of birds within each of the three distance to the coast classes. Atlantic Puffins tended to aggregate near the shelf edge (mean ± SD = 29.0 ± 22.2 km) whereas the majority of Razorbills and Common Murres were observed less than 10 km from the coastline (mean ± SD = 5.7 ± 3.2 km and 7.2 ± 3.9 km respectively).

Estimate of acute seabird mortality due to the Prestige oil spill

Our estimate is that 87,594 alcids were killed by the *Prestige* oil spill disaster off Galicia, of these 48% were Common Murres, 28% Atlantic Puffins and 23% Razorbills (Table 1). Our estimate is higher than standard estimates based on direct extrapolations from recovery rates of drift experiments conducted at other times and places (see Appendix). The mean recovery rate of the 35 drift experiments we reviewed is 0.177 (CI: 0.124–0.236). When only the subset of drift experiments aimed at alcids and/or all seabirds was considered (n = 19) the recovery rate was 0.145 (CI: 0.070–0.234). These recovery rates result in a mortality estimate of 55,608 and 67,719 alcids, respectively.

Comparison with other oil spills

Published mortality figures from other marine oil spills which used analogous estimation methods (8 oil spills; see Fig. 5) suggest that seabird mortality was not affected by the amount of oil released ($F_{1,7} = 0.01$, $P = 0.99$). The *Prestige* figures are within the same order of magnitude of the highest seabird mortality estimates ever reported for an oil spill worldwide; moreover, the

Table 1. Estimates for alcid mortality in Galicia in the aftermath of the *Prestige* oil spill.

Species	Carcasses reported	Mortality estimate (number of birds killed)	
		Mean	Confidence interval
Common Murre	4,492	42,321	79,614–25,856
Atlantic Puffin	2,861	24,662	46,752–15,139
Razorbill	2,473	20,611	35,948–13,118
Total alcids	9,826	87,594	54,113–162,313

Note: Confidence intervals were calculated as 2.5% (lower) and 97.5% (upper) percentiles in bootstrapped distributions.

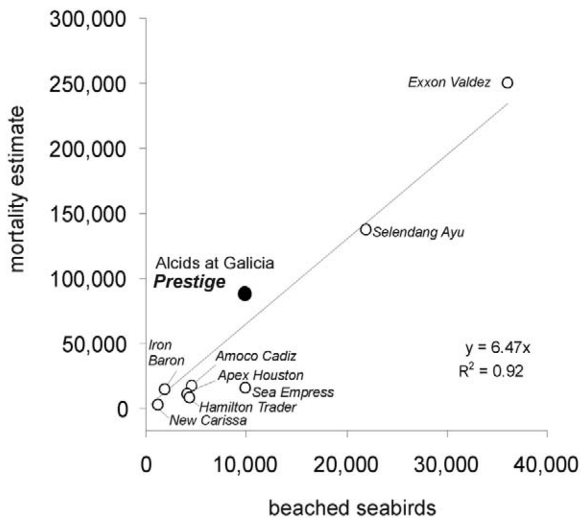

Fig. 5. Regression between the numbers of beached seabirds reported and mean estimates of actual seabird mortality (number of seabirds killed) in oil spills were mortality was assessed through drift experiments. *Exxon Valdez* (Piatt and Ford 1996); *Selendang Ayu* (Byrd and Reynolds 2007); *Iron Baron* (Goldsworthy et al. 2000); *Hamilton Trader* (Burger 1993); *Amoco Cadiz* (Monnat 1978); *Apex Houston* (Page et al. 1990); *Sea Empress* (Camphuysen et al. 2005).

estimated mortality was higher than expected by the number of carcasses retrieved (Fig. 5).

Discussion

We present an estimate of the short-term acute mortality of seabirds caused by the *Prestige* oil spill, one of the largest perturbations of its type in the marine ecosystems of the North Atlantic. It was based on real-time drift block experiments conducted in Galicia, the area most affected by the oil spill during the period when, as suggested by beached bird survey data, seabird mortality due to oiling was at its peak. According to our results, about 100,000 alcids (54,113–162,313) were killed off Galicia in the aftermath of the *Prestige* oil spill (see Table 1). Our study strongly suggests that estimates that rely on drift block experiments and the number of oiled seabirds reported from beach surveys should incorporate: (1) Spatial variation in the recovery rates of drift blocks. For nine release points in the marine area affected by the spill the recovery rates of drift blocks varied from 4.0 to 40.8% with a significant effect of distance to the coast. (2) Differences in detectability between beached carcasses and drift blocks. According to our results the probability of a beached drift block being reported by the beach survey program set in response to the spill in Galicia was 53% higher compared to that of seabird carcasses, therefore the use of drift block data may result in a significant underestimation of mortality if not corrected for detectability. (3) Data on the distribution of the seabird species involved. Species that tend to concentrate in the distance strata with low recovery rates will tend to be underrepresented in the beach survey counts thus leading to the underestimation of their actual mortality.

Comparison with other oil spills

Even though our estimate is only reliable for alcids in Galicia, it indicates that the *Prestige* oil spill, in terms of acute seabird mortality, was one of the worst oil spills ever recorded worldwide, similar to *Exxon Valdez* (100,000–690,000; Piatt and Ford 1996), *Stylis* (200,000–300,000; Camphuysen et al. 2005), *Erika* (120,000–300,000; Camphuysen et al. 2005), and *Selendang Ayu* (137,000; Byrd and Reynolds 2007). Note that 52.3% of the oiled seabirds were collected in Galicia and that alcids comprised 81.7% of the beached seabirds reported in the whole spill area (Portugal, Spain and France); although not quantified, the total short-term acute seabird mortality due to the *Prestige* oil spill is likely to exceed 200,000 seabirds. One possible explanation for the comparatively high mortality caused by the *Prestige* was the vast offshore oil front generated by the wreck.

Methodological issues

Estimates of acute seabird mortality in the aftermath of an oil spill must take into account several sources of uncertainty. The first of these concerns variation over time within and between areas in the environmental conditions that determine both the number of seabirds washed ashore and the outcomes of drift experiments. The study area is highly influenced by the marked seasonality of winds with two mean seasons: upwelling season from April to September (northerly NE offshore winds) and downwelling season from October to March (southerly SW inshore winds). Though there is interannual variability in the intensity of the seasons and in the timing of the transition between them, the oceanographic conditions within seasons are fairly constant. The first spring upwelling pulse in Galicia (i.e., the end of the downwelling season) took place at the end of March (Ruíz-Villarreal et al. 2006). This means that our study and the *Prestige* oil spill occurred within the downwelling season of 2002–03. It is therefore likely that our assessment of recovery rates (15 January–8 February) was representative of the oceanographic conditions that prevailed during the period of peak mortality for marine birds: 16 November–5 March, when over 95% of the total number of oiled seabirds were reported from beach surveys. Moreover, note that wind speed and wind direction during our experiments was not different from the rest of the period of high seabird mortality. In wooden blocks and seabird carcasses drift direction and velocity is strongly influenced by wind action (Flint and Fowler 1998 and references therein; see also Castege et al. 2007). In the case of the *Prestige* oil spill, the surface circulation during the downwelling season was to the north and east, even during the infrequent headwind pulses (Álvarez-Salgado et al. 2006, Ruíz-Villarreal et al. 2006), thus favoring the deposition of drifting objects into beaches. *Prestige* oil patches in open ocean waters of the Galician basin were displaced by the wind blowing over the surface layer with a velocity of 2% the wind speed and rotated clockwise 5° from the wind direction (Álvarez-Salgado et al. 2006). The blocks we dropped off Galicia drifted accordingly towards the east and north.

With the likely exception of Northern Portugal where oceanographic conditions are similar to Galicia, the results of our drift experiments cannot be directly applicable to the rest of the oiled littoral. In the Gulf of Biscay, the oceanographic conditions that prevailed during the *Prestige* crisis reduced the probability of oiled seabirds being washed ashore (see González et al. 2008). Indeed, the results of two other drift block experiments suggest that in the Cantabrian Sea and elsewhere in the Gulf of Biscay recovery rates were much smaller compared to Galicia (note that in the Cantabrian Sea southerly winds are offshore winds). In Aquitaine (France, Fig. 2), realized recovery rates of Common Murre corpses released at sea (one out of 121) were two orders of magnitude smaller (see Castege et al. 2007) compared to Galicia. Moreover, in an additional experiment we conducted in Asturias (Cantabrian Sea, Fig. 2) on February 2003, the recovery rate of drift blocks was virtually null because the first block was reported well beyond the sinking time for drifting oiled carcasses as estimated by different studies (Castege et al. 2007; see Wiese 2003 and references therein). Our results suggest that in the *Prestige* case, including all block recoveries without a cut-off period leads to the underestimation of seabird mortality. Interestingly, the beach cast experiment revealed that at least two days should be allowed for blocks to be reported once beached. Having this into consideration and based on the floating time for seabird carcasses reported by others, the lapse we allowed for drifting blocks (23 days) seems quite realistic.

Even in instances when they reach the coast in a relatively short time, some oiled seabirds are likely to go unreported due to reasons related to detectability, searching effort and removal by scavengers (e.g., Van Pelt and Piatt 1995, Ford 2006). Beached bird surveys in Galicia were intense and comprehensive during the first five months of the spill as virtually all beaches were searched by trained volunteers on a daily basis up to the end of March (see Fig. 3). Therefore, our assessment of beach survey effort (10–18 February) was likely representative of the quality and intensity of the beached bird survey scheme that was established in Galicia in response to the *Prestige*. Surprisingly, the outcomes of our experiment at beaches suggested that despite the huge searching effort involved, a considerable proportion of the beach washed drift blocks and seabird carcasses may go unnoticed (30.6% and 54.6% respectively). Interestingly, tagged blocks were more likely to be reported than alcid carcasses, therefore suggesting that, when using drift blocks, there is a risk to grossly underestimate mortality if differences in the reporting probability between blocks and seabird carcasses are not properly assessed. It is unclear however if the higher rates of recovery for drift blocks compared to seabird carcasses in Galicia were due to scavenging, differences in detectability or because beached drift blocks were easier to report.

Conducting drift experiments during a spill can be a useful way to estimate acute seabird mortality because recovery rates will reflect actual oceanographic conditions and search effort at the time of the spill; this requires however some degree of knowledge on the distribution of vulnerable seabird populations (Wiens and Parker 1995, Wilhelm et al. 2007). Our estimation relies on data from ship surveys that were performed in the winters of 2004–05 and 2005–06, two and three years after the spill. It cannot be assumed that these surveys reflected the actual distribution and abundance of alcids at the time of the spill. Nevertheless, the variable used here, distance to the coast, is likely to show less interannual variation as it is related to differences among species in their at-sea behavior and foraging preferences, as shown by other studies (Brown 1985, Huettmann et al. 2005).

Conclusions

The *Prestige* oil spill disaster was a huge pulse perturbation at a scale that over passed that of a Large Marine Ecosystem (LME) (⟨http://www.lme.noaa.gov/⟩; see Sherman and Skjoldal 2002). Oil pollution, lethal to seabirds, extended across the northern half of the Iberian Coastal LME killing large numbers of wintering seabirds with a potential effect on the demography of populations located at the center of the Celtic-Biscay Shelf LME, as has been documented for Common Murres (Votier et al. 2005, 2008). All ringed alcids ($n = 137$) collected during the *Prestige* oil spill originated from breeding colonies of Britain and Ireland (Moreno-Opo et al. 2003); thus adverse impacts of the *Prestige* oil spill on British populations of these species are expected. Importantly, the number of Atlantic Puffins killed was higher than expected according to the number of carcasses reported from beaches due to their rather offshore distribution.

When dealing with the assessment of the impacts of accidental events such as oil spills, perfect experimental design is not possible, and the methodological issues and ecological assumptions associated with different study designs become especially important (Wiens and Parker 1995). We found that ignoring some uncertainties (e.g., detectability) might bias the mortality estimates. Quantitative evaluations of the ecological effects of large-scale perturbation pulses are subject to great uncertainty due to lack of data and too little knowledge of the system (Cressie et al. 2009, O'Riordan and Jordan 1995). Efforts to take advantage of such events should therefore be welcomed, as this will mean progress in the research of ecosystem response to stress and perturbation at scales that often fall way beyond experimentation. This however requires a clear commitment, including pre-spill readiness and preparation. We recommend that drift block assessments of seabird mortality should be included in contingency response plans to oil pollution emergencies; therefore, a supply of drift-blocks designed to mimic the drifting behavior of the marine bird species of interests should be at hand. Our study suggests that it is crucial to evaluate temporal and spatial variations in drift recovery rates during the spill; and, importantly, drift block detectability.

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Appendix

Table A1. Review of carcass drift and drift block experiment results. Data from the two experiments reported in this paper are shown for comparative purposes.

Ocean	Region	No. items	Target species	Recovery (%)	Sources
Atlantic	England	...	shags	25.0	Coulson et al. 1968[2]
Atlantic	British Isles	130	cormorants	14.6	Harris and Wanless[1]
Pacific	California	186	gulls	29.9	Page et al. 1982[1]
Atlantic	British Isles	...	gulls	10.0	Bibby and Lloyd 1977[1]
Atlantic	British Isles	300	gulls	11.0	Bibby and Lloyd 1977[1]
Atlantic	British Isles	305	gulls	44.0	Bibby and Lloyd 1977[1]
Atlantic	British Isles	347	gulls	59.0	Bibby and Lloyd 1977[1]
Atlantic	British Isles	144	gulls	20.0	Hope-Jones et al. 1978[1]
Atlantic	British Isles	600	gulls	9.8	Bibby 1981[1]
Atlantic	British Isles	40	gulls	40.8	Stowe 1982[1]
Atlantic	British Isles	150	gulls	11.2	Stowe 1982[1]
Pacific	Alaska	152	seabirds	61.0	Flint and Fowler 1998
Pacific	Alaska	150	seabirds	0.7	Flint and Fowler 1998
Pacific	Alaska	165	seabirds	16.0	Byrd and Reynolds 2007
Atlantic	Newfoundland	120	seabirds	7.0	Chardine and Pelly 1994[2]
Pacific	California	63	alcids	0	Page et al. 1982[1]
Pacific	British Columbia	...	alcids	43.0	Hlady and Burger 1993[2]
Pacific	British Columbia	...	alcids	53.0	Hlady and Burger 1993[2]
Pacific	British Columbia	...	alcids	10.0	Hlady and Burger 1993[2]
Pacific	Alaska	100	alcids	3.0	Piatt et al. 1990[1]
Pacific	Alaska	184	alcids	8.0	ECI 1991[1]
Atlantic	Newfoundland	115	alcids	0	Threlfall and Piatt 1982[1]
Atlantic	Newfoundland	129	alcids	0	Threlfall and Piatt 1982[1]
Atlantic	Newfoundland	400	alcids	0	Threlfall and Piatt 1982[2]
Atlantic	Newfoundland	600	alcids	24.0	Threlfall and Piatt 1982[2]
Atlantic	British Isles	410	alcids	20.0	Hope-Jones et al. 1970[1]
Atlantic	British Isles	319	alcids	7.5	Lloyd et al. 1974[1]
Atlantic	British Isles	238	alcids	5.0	Parr et al. 1997
Atlantic	North Sea	200	seabirds	24.5	Seys 2001
Atlantic	North Sea	93	seabirds	15.1	Seys 2001
Atlantic	North Sea	107	seabirds	0	Seys 2001
Atlantic	North Sea	76	seabirds	10.5	Seys 2001
Atlantic	North Sea	121	seabirds	0	Seys 2001
Atlantic	North Sea	37	seabirds	16.2	Seys 2001
Atlantic	France	121	Murres	0.8	Castege et al. 2007
Atlantic	Asturias	150	alcids	16.7	This paper
Atlantic	Galicia	438	alcids	16.5	This paper

Note: 1, taken from Piatt and Ford (1996): Table 1; 2, taken from Wiese and Jones (2001): Table 1.