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How Many Seabirds Were Killed by the *Exxon Valdez* Oil Spill?

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Abstract.—After the *Exxon Valdez* oil spill of 24 March 1989, 36,115 dead seabirds were recovered from beaches and processed at morgues. Most or all of 1,888 live oiled seabirds brought to rehabilitation centers also died and about 3,260 oiled carcasses were never delivered to morgues. Of these 41,263 carcasses accounted for, we estimated conservatively that only 30,000 were killed by oil pollution. Carcass drift and recovery experiments conducted in the affected area during the spill and 1 year later, along with historical experiments conducted in other oceanographic regions, suggest that only a fraction (range = 4–30%) of birds killed were likely to have been recovered from beaches. Regression analysis of these drift–recovery data predicts a 15% recovery rate ($r^2 = 0.38$, $P = 0.015$). We recognize uncertainties in the assumptions and parameter values used to extrapolate total mortality from drift–recovery data, but we have confidence that mortality fell within the extreme range of estimates (100,000–690,000 birds killed) because these reflect a very wide range of observed and experimentally determined parameter values. Total mortality can also be estimated by comparing pre- and postspill colony population estimates. Uncertainties about these census data are greater than those associated with drift–recovery data, but nonetheless provide an independent mortality estimate of similar magnitude. Taken together, all evidence suggests that about 250,000 seabirds were killed by *Exxon Valdez* oil.

It is difficult to measure the total mortality of seabirds from oil pollution. The number of oiled-bird carcasses found on beaches typically represents only a fraction of the total killed, because some sink at sea or drift offshore, and those that drift ashore may be removed rapidly by scavengers or be buried in sand and debris. Furthermore, the timing, frequency, and thoroughness of beach surveys determine the number of oiled carcasses likely to be counted. The ratio of birds recovered to those killed is a function of all these factors and is usually quite low (Ford et al. 1987).

There are three general approaches to estimating total seabird mortality resulting from an oil spill: (1) measuring the difference between pre- and postspill colony populations, (2) estimating carcass loss and recovery rates from experimental drift studies conducted during the actual spill, or (3) extrapolating from carcass drift and recovery experiments conducted at other times or places.

Estimating mortality from changes in colony population size is intuitively appealing but problematical. The effects of a spill (especially in winter) may be spread over many distantly spaced colonies, and postspill censuses may be difficult to interpret because of attendance by previously nonbreeding birds and immigrants from other colonies (Stowe 1982). Furthermore, colony censuses do not include the component of the population located at sea during the census, which can be larger than the component attending nest sites (Piatt and Ford 1993). Finally, prespill baseline data on colonies and associated populations at sea may be inadequate for statistical evaluation of population changes.

Estimating total mortality from carcass drift experiments does not require baseline data; however, processes governing the loss and recovery of carcasses vary considerably over time within and between areas, and it is often difficult to retroactively assess conditions that prevailed at the time of a spill. Conducting drift experiments during a spill (e.g., Hope-Jones et al. 1978) may be the best way to estimate total mortality because the recovery rates of marked carcasses will reflect actual oceanographic conditions and search effort at the time of the spill; however, this requires some degree of prespill readiness and knowledge of the distribution of spilled oil and birds at the time of the spill.

After the *Exxon Valdez* oil spill of 24 March 1989, 36,115 dead seabirds were recovered from beaches and processed at morgues. This was the highest recovery of carcasses ever documented after an acute oil pollution event (Piatt and Lensink 1989). In addition, most or all of 1,888 live oiled seabirds brought to rehabilitation centers also died (Piatt et al. 1990) and about 3,260 oiled carcasses were never delivered to morgues because they were discarded, burned, or buried (Piatt et al. 1990; Ecological Consulting, Inc. [ECI] 1991). Anecdotal reports suggested that thousands more carcasses were not accounted for (e.g., sucked into oil skimmers, otherwise recovered but discarded).

Based on the timing of recoveries, degree of oiling, and species composition, it was estimated conservatively (Piatt et al. 1990; ECI 1991) that about 30,000 of the total 41,263 carcasses accounted for died from oil pollution. Most of these were murres *Uria* spp. (74%), other alcids (7%), and seaducks (5.3%). After 1 August, most (72%) carcasses recovered were shearwaters and gulls that apparently died from natural causes (starvation). This die-off in late summer added uncertainty to the cause of death of other birds retrieved at that time. Thus, all specimens processed at morgues after 1 August were excluded from the tally of oil-killed birds even though some (e.g., including 702 seaducks and 440 murres) had probably been killed by oil and died earlier in summer (Piatt et al. 1990).

Based on this conservative estimate of birds killed by oil, and several drift–recovery experiments, initial extrapolations of total mortality ranged in the low hundreds of thousands of seabirds (100,000–300,000 by Piatt et al. 1990; 300,000–645,000 by ECI 1991). Despite extensive documentation in these original reports of the underlying assumptions and sources of uncertainty in the extrapolations, the high-end ranges of these estimates have been selectively quoted or criticized (e.g., Parrish and Boersma 1995a) in the popular press and used by some biologists as a basis for assessing impacts on populations. At the other extreme, even the low-end mortality estimates have been challenged because of uncertainties associated with them (Wells et al. 1995; Wiens 1995; Parrish and Boersma 1995a). Indeed, these biologists argue that only those carcasses recovered from beaches should be used to assess population impacts of the *Exxon Valdez* oil spill.

Thus, more than 6 years after the *Exxon Valdez* oil spill, we again ask the questions: What is a reasonable estimate of the number of seabirds killed, and how much confidence can we have in that estimate? In this article, we reevaluate our estimates of total mortality with respect to their underlying assumptions and conclusions and compare these with alternative estimates of mortality from other drift experiments and colony census data. Finally, we make some recommendations for estimating seabird mortality in future oil spills.

Estimating Total Seabird Mortality

Real-Time Drift Experiments

Most seabird mortality from the *Exxon Valdez* oil spill occurred during the 2 months after the spill on 24 March, although dead and dying birds were recovered from beaches for more than 5 months afterward (Piatt et al. 1990). A carcass drift experiment was initiated in Prince William Sound in April, but this experiment was aborted by administrators in the U.S. Fish and Wildlife Service because of negative public response (ECI 1991). Forty-seven carcasses were color-banded and released within 200 m of shore in western Prince William Sound. No banded birds were ever recovered; however, morgue attendants were never asked to look for bands, and extensive oiling of carcasses may have precluded their discovery.

Another drift experiment was conducted in the Gulf of Alaska about 6 weeks after the initial spill to estimate recovery rates (Piatt et al. 1990). Old (approximately 2–4 weeks), mousse-covered carcasses (N = 100; 89% murres) were recovered off a beach in Puale Bay along the Alaska Peninsula, cleaned of several inches of caked-on mousse, marked with wired "please report" tags that extended away from the body, and released at the Barren Islands in early May. Only three murres (3%) were later recovered, all from the very same beach in Puale Bay. This strongly suggested that prevailing currents had originally (in late April) carried oiled birds to this area from lower Cook Inlet.

Old carcasses sink faster than fresh ones (Burger and Fry 1993), and search effort on the remote beaches along the Alaska Peninsula was incomplete outside of Puale Bay (ECI 1991). Furthermore, most birds recovered west of the Kenai Peninsula (approximately 75% of total) were encased in thick mats of oil mousse, an emulsion that consists largely of trapped air and conceivably added buoyancy to the original bird carcasses.

For these reasons, Piatt et al. (1990) considered the 3% experimental recovery rate to be minimal. Also considering drift experiments conducted elsewhere in the world (Table 1), the estimated size of populations at risk, and the fact that a minimum 3% recovery was observed in the most distant recovery site (and was therefore likely to be much higher in areas closer to the spill source), the spillwide recovery rate was estimated conservatively at 10–30%, suggesting that 100,000–300,000 birds were killed by the oil spill (Table 2).

The problem with this estimate is that factors influencing recovery rates (such as survey effort,

TABLE 1.—Observed and estimated rates of recovery of seabirds on beaches from 17 carcass drift experiments. Predominant species used in experiments included alcids (a), gulls (g), and cormorants (c).

Region	Species	*N*	Recovery (%)	Reference
Irish Sea	a	410	20.0	Hope-Jones et al. (1970)
Irish Sea	a	319	7.5	Lloyd et al. (1974)
Bristol Channel	g	Unknown	10.0	Bibby and Lloyd (1977)
Irish Sea	g	300	11.0	Bibby and Lloyd (1977)
Irish Sea	g	305	44.0	Bibby and Lloyd (1977)
Irish Sea	g	347	59.0	Bibby and Lloyd (1977)
English Channel	g	144	20.0	Hope-Jones et al. (1978)
North Sea	g	600	9.8	Bibby (1981)
North Sea	g	40	40.8	Stowe (1982)
North Sea	g	150	11.2	Stowe (1982)
North Sea	c	130	14.6	Harris and Wanless (in press)
California	g	186	29.9	Page et al. (1982)
California	a	63	0.0	Page et al. (1982)
N. Grand Banks	a	115	0.0	Threlfall and Piatt (1982)
S. Grand Banks	a	129	0.0	Threlfall and Piatt (1982)
Gulf of Alaska	a	100	3.0	Piatt et al. (1990)
Gulf of Alaska	a	184	8.0	ECI (1991)
Total and mean		3,522	17.0	

sinking rates, scavenging rates, etc.) varied geographically, and the results of the drift experiment were directly applicable to only a portion of the affected region. As stated in Piatt et al. (1990), this conservative estimate of total mortality was put forward "tentatively" until such time that specific parameters needed to model total mortality could be measured. This was undertaken in summer 1990 by ECI (1991).

Postspill Drift and Carcass Experiments

In 1990, a series of carcass drift experiments were conducted in Prince William Sound and southeast of Kodiak Island in order to estimate some of the parameters needed to back-calculate total mortality (ECI 1991; Ford et al. 1996, this volume). In this study, fresh seabird carcasses ($N = 184$; 89% alcids) were coated with oil, radio-tagged, and released at sea. Subsequent drift and sinking rates were determined, and separate experiments to assess scavenging and disappearance rates on beaches were also conducted. Beach survey effort during the original spill was estimated from historical records.

TABLE 2.—Estimates of total seabird mortality from the *Exxon Valdez* oil spill.

Source	Estimate Minimum	Mean	Maximum
Piatt et al. (1990)	100,000	200,000	300,000
ECI (1991)[a]	300,000	435,000	645,000
Drift experiments[b] ($N = 15$)	116,000	200,000	690,000
Murre colony data	51,000	146,000	241,000

[a]Minimum and maximum estimates include 95% of possible outcomes from 1,250 Monte Carlo simulations.

[b]Minimum and maximum estimates are 95% confidence limits.

Using the best estimates of input parameters, the joint probability of recovery was estimated at 8%, suggesting that 375,000 birds were killed. Using a range of possible values for each parameter estimate, the mean probability that a carcass would have been recovered was calculated by Monte Carlo analysis to be about 6.9%, suggesting that 435,000 (range, 300,000–645,000) seabirds died as a result of the spill (ECI 1991; Ford et al. 1996). The model was most sensitive to "sinking rate" and "persistence on beach" parameters.

There remain uncertainties about some parameter values, and there are gaps in our understanding of processes controlling the recovery of dead seabirds. If we could refine some parameter values, estimates of total mortality would probably decrease or increase, as the following examples suggest: (1) The results of drift experiments were highly variable (Table 1) and were determined largely by prevailing conditions at the time of a spill; were results obtained from experiments in 1990 applicable to the spill in 1989? Weather conditions were more severe in 1989 than during the study in 1990, and therefore the 1990 at-sea loss experiments may have underestimated actual losses in 1989. (2) Was the use of persistence rates obtained from experimental studies using dozens of carcasses applicable to the situation after the *Exxon Valdez* oil spill? Persistence rates obtained from recent study of a large (tens of thousands) murre die-off in Resurrection Bay in March 1993 (Piatt and van Pelt 1993; van Pelt and Piatt 1995) suggest a higher persistence rate (89–96%/d) than the range of values used in the ECI model (54–83%/d). Use of these data would increase the estimated probability of carcass recovery and decrease the estimate of total mortality. (3) How efficiently were beaches checked for carcasses? Because data were not available, Ford et al. (1996) assumed 100% efficiency in locating carcasses, but unpublished studies conducted during the Amoco Cadiz oil spill suggested that beach surveys were only about 80% efficient under conditions that were more benign than those encountered by searchers after the *Exxon Valdez* oil spill. Furthermore, anecdotal reports from many areas of the Gulf of Alaska indicated that burial of carcasses in sand and gravel was frequent and may have "removed" 10–20% of carcasses from some beaches before searchers could recover them (ECI 1991). Incomplete recovery of carcasses from beaches would lead to underestimates of total mortality. (4) Did mousse-caked birds in 1989 (see above) have a lower sinking rate than oil-soaked birds in 1990? If so, then estimates of the at-sea loss of carcasses in some regions would be decreased, with a corresponding increase in estimates of total mortality. Experimental evaluation of these factors during future oil spill incidents would improve the accuracy of postspill mortality estimates.

Comparison of Real-Time and Postspill Experiments

There is at least one direct comparison to be made between the drift experiment conducted by Piatt et al. (1990) during the spill and that of ECI (1991) conducted in the following year. Based on the estimated parameter values in different areas, the ECI model (ECI 1991: 152) determined that the highest recovery rates would have occurred in Prince William Sound (35%) and at the Barren Islands (49%). Cook Inlet (21%) and Kenai Fjords National Park (14%) had intermediate recovery rates. Kodiak Island (6%) and the Alaska Peninsula (2%) had the lowest calculated recovery rates—largely because of the long periods of time carcasses would have been at sea and because of a relatively low level of search effort. Piatt et al. (1990) actually observed a 3% recovery rate along the Alaska Peninsula. Thus, despite uncertainties in assumptions of both studies, they were in remarkably good agreement about recovery rates along the Alaska Peninsula, providing some confidence that independent drift studies can yield repeatable results.

Nevertheless, the difference of 1% is noteworthy because 30% (N = 8,881) of all birds were recovered along the Alaska Peninsula and the extrapolation factor is very large. Thus, using the observed 3% recovery rate rather that the calculated 2% recovery rate would decrease the ECI best estimate of total mortality by 40% to about 227,000 birds. This is a simplistic analysis, however, because the ECI model calculates site-specific recovery rates along the peninsula, and 2% is an average value used for geographic comparisons. Nonetheless, it illustrates the need for caution when using low recovery rates to estimate total mortality.

Other Drift Experiments

Carcass drift and recovery experiments have been conducted in a variety of locations around the world (Table 1). Most of these experiments involved dropping marked carcasses at various distances offshore in regions where systematic beach surveys were being conducted (e.g., Bibby and Lloyd 1977; Page et al. 1982; Threlfall and Piatt 1982). Some were conducted during actual oil spills (e.g., Hope-Jones et al. 1978). In one case, a "natural" experiment involved the deaths and subsequent beach-recoveries of color-ringed cormorants after a large die-off of cormorants and murres at a well-studied colony (Harris and Wanless, in press). Finally, the recovery rate provided by ECI (1991) is actually a composite best estimate calculated from a number of independent experiments on drift, sinking, persistence, and so forth of oiled carcasses (see Ford et al. 1996).

The average (mean, 17%; median, 11%) recovery rate from all 17 studies is quite low (Table 1). Results indicate that recovery rates are highly dependent on local wind, sea, and current conditions at the time of the experiment (see especially Bibby and Lloyd 1977) and should be applied to particular spills with caution. Highest recovery rates have been observed where carcasses were released relatively close to shore during periods of onshore winds (Bibby and Lloyd 1977) or within confined oceanographic areas (e.g., the Irish Sea). Furthermore, gull carcasses typically have a higher recovery rate (10–59%) compared to those of alcids (0–20%), possibly because they are more buoyant and present more profile for wind-drift (Bibby and Lloyd 1977; Page et al. 1982).

Can drift experiments conducted at various times and locations be used to predict recovery rates in the case of the *Exxon Valdez* spill? Despite the many sources of variability, linear regression (Figure 1) of experimental drift data reveals that 31% of the variance in carcass recoveries can be accounted for

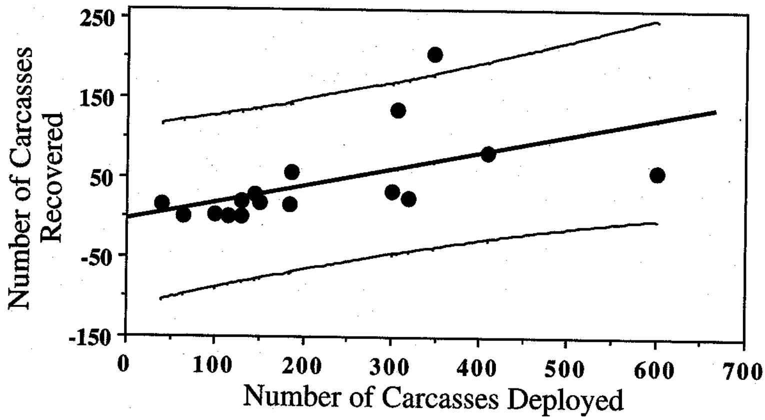

FIGURE 1.—Linear regression of seabird carcass recovery data from 16 drift experiments (Table 1; Bristol Channel data are not included because of unknown number of carcasses released). The best-fit regression line is bounded above and below by 95% confidence limits.

by the number of carcasses released ($N = 16$, $r^2 = 0.31$, $P = 0.025$). Note that the Bristol Channel data (Table 1) could not be included in this analysis because the number of carcasses released was unknown. The slope (0.209) of the regression line predicts a 21% recovery rate. If the lone outlier (above the upper 95% confidence limit in Figure 1) is removed from the analysis, the predicted recovery rate declines to 15% and the explained variance increases to 38% (slope $\pm$ SE = 0.151 $\pm$ 0.054, $N = 15$, $r^2 = 0.38$, $P = 0.015$). Removal of this outlier is justified because it was derived from an experiment in which gull carcasses were released relatively close to shore during a period when sustained winds were blowing directly into a large embayment (eastern Irish Sea; Bibby and Lloyd 1977). The next highest recovery rate (Figure 1, Table 1) was obtained under similar experimental conditions, but as it fell within the 95% confidence limits in the original analysis, we retain it in the final analysis. (Further removal of this data point would increase explained variance to 57% and decrease the predicted recovery rate to 12% at $P = 0.002$.)

Using a predicted recovery rate of 15%, we can therefore estimate that about 200,000 seabirds were killed by *Exxon Valdez* oil (Table 2). The range of predicted mortality (116,000–690,000; Table 2) is similar to that reported by ECI (1991). In any case, using these combined experimental data to predict mortality for the *Exxon Valdez* spill probably underestimates the true mortality because (1) most mortality occurred in open waters of the Gulf of Alaska, (2) search effort was relatively poor in this region (ECI 1991), (3) alcids were the predominant species affected, and (4) all these factors are known to decrease recovery rates.

Murre Colony Population Counts

It is also possible to make an estimate of the total mortality of seabirds from the spill by comparing pre- and postspill colony counts of murres (see Tables 1 and 2 of Piatt and Anderson 1996, this volume). Uncertainties associated with colony count data (see discussion in Piatt and Anderson 1996) are probably much greater than those associated with drift experiments, but it is worth examining these data for comparative purposes because they are an independent source of information about pre- and postspill seabird population changes.

Colony count data indicate that murre populations declined by 7–48% at individual colonies in the path of the spill (Nysewander et al. 1993; Piatt and Anderson 1996). Overall, "affected" murre populations declined by approximately 40% between pre- and postspill censuses; however, it appears that populations were already declining at some major colonies before the spill occurred, and not all of this decline should be attributed to the spill (Piatt and Anderson 1996). For example, murre populations at Puale Bay (in the spill path) declined by 5.8% per annum and at Chisik Island (in the spill region but outside the direct path) by about 7.5% per annum in years before the spill.

It is possible to calculate the maximum impact of the spill on Gulf of Alaska murre populations if we assume that: (1) declines at specific colonies occurred throughout the pelagic areas in which they were located; (2) all declines resulted from the oil spill (probably not true, see above); (3) colony counts include only birds found at the colony at the time of censusing, and about 1.4 times as many colony-associated birds (nonbreeders, subadults, etc.) are found at sea (Piatt and Ford 1993); (4) nonattending birds at sea were killed in the same proportion as those at colonies; and (5) no birds killed by the spill were in transit from areas unaffected by the spill.

The data suggest that the total population (at colony and at sea) of murres in affected areas declined by 178,490 birds between years before the spill (1975–1988) and years after the spill (1989–1991) (see Table 2 in Piatt and Anderson 1996). This represents the maximum possible number of murres that could have been killed by *Exxon Valdez* oil. Because 74% of all birds killed were murres (Piatt et al. 1990), this suggests that a maximum of about 241,200 (178,490/0.74) marine birds of all species were killed by oil. Historical data suggest, however, that murres were declining at some colonies before the spill, so the real number killed by the spill must be some fraction of this maximum estimate. For example, if the 5.8% per annum decline observed at Puale Bay before the spill persisted through and after the spill, then only 10% of the observed 48% decline there is unaccounted for by this trend. By extension, a minimum of about 37,500 (0.21×178,490) murres were killed by oil, and by further extrapolation, 50,650 birds of all species. Thus, the total bird kill estimated from colony censuses ranges from about 51,000 to 241,000 birds, depending on the assumptions used. The average of these estimates is 146,000 birds killed (Table 2).

The error associated with colony counts cannot be assessed with existing data (Piatt and Anderson 1996). Aside from that issue, the estimates of mortality from census data are probably underestimates because one assumption (number 5 above) is probably invalid. During the time (April–May) that oil was widely dispersed in the Gulf of Alaska, it was highly likely that many seabirds were in transit through the spill zone en route to colonies outside the spill zone (Piatt et al. 1990). Losses of these birds would not have been reflected at colonies censused within the spill zone.

Conclusions

Mean estimates of total seabird mortality (200,000–435,000) based on various drift experiments are all in general agreement as to the order of magnitude of the kill (Table 2). Although the individual estimates each depend on some uncertain assumptions, we have confidence that total mortality fell within the range of extreme estimates (i.e., 100,000–690,000) because these reflect a very wide range of observed or experimentally determined parameter estimates.

The estimated mortality derived from murre colony counts includes many potential sources of error that cannot be evaluated. Nonetheless, census data suggest a similar level of mortality as do drift experiments. Census data further suggest that if the highest estimate of seabird mortality (690,000) is correct, then the kill must have included many individuals in transit through the spill area because otherwise the entire prespill population of murres in the spill zone (approximately 446,000) would have been eliminated, which was not the case (Table 2; Piatt and Anderson 1996).

Taken together (Table 2), the evidence suggests that about one-quarter of a million seabirds died in the aftermath of the *Exxon Valdez* oil spill, which is by far the highest estimated level of seabird mortality ever reported from an acute oil spill (Piatt and Lensink 1989).

In a selective review of the evidence, Parrish and Boersma (1995a) assert that our estimates of total mortality were exaggerated and unscientific. We find it ironic that these statements are made in a non-peer-reviewed popular science magazine. Considering our conservative estimates of the proportion of recovered birds actually killed by oil and our clearly documented, conservative (and peer-reviewed) projections of total mortality (Piatt et al. 1990; ECI 1991; Ford et al. 1996), we are at a loss to understand the basis of Parrish and Boersma's conclusions. In contrast, their own "assessment" of mortality estimates (Parrish and Boersma 1995a) did not even reference Ecological Consulting, Inc.'s critical 1990 study nor mention even one of the many drift experiments conducted worldwide that clearly support the conclusion that only a fraction of seabirds were likely to have been recovered (Piatt 1995). Faced with these criticisms (Piatt 1995), Parrish and Boersma asserted (1995b) that drift experiments are much too variable to use for interpreting impacts of the *Exxon Valdez* oil spill. Again, the scientific facts (Figure 1 and above) are at odds with their opinions. We submit that Parrish and Boersma's assessment is seriously flawed and subjective.

In conclusion, a preponderance of evidence indicates that only a fraction of the seabirds killed by

Exxon Valdez oil were ever recovered from beaches. The exact proportion recovered will never be known, but to dismiss the range of possible mortality estimates as mere claims (Parrish and Boersma 1995; Wells et al. 1995) and insist on using only the number of birds retrieved from beaches as the basis for evaluating population impacts (Table 1 in Wiens 1995) is simply not credible: It ignores a large body of quantitative information and accepts an estimate that is severely biased in a known direction. On the other hand, stressing the high-end estimates of mortality ignores recognized uncertainties and accepts a known bias in the opposing direction.

Assessing the impacts of future oil spills on seabird populations is likely to include all the difficulties observed in the case of the *Exxon Valdez* spill. The kind of detailed baseline data needed to assess population changes at seabird colonies is rarely available to assess damages from acute or chronic oil pollution (Piatt et al. 1991); however, our understanding of processes affecting the recovery rates of seabirds from beaches has advanced considerably in recent years (Ford et al. 1987, 1996; Burger and Fry 1993; van Pelt and Piatt 1995), thereby providing a quantitative basis for estimating the population impacts of oil pollution.

We need to conduct more research on these processes so that we can better estimate those parameters that determine recovery of carcasses. More importantly, we should be prepared to conduct realtime drift experiments in the event of future oil spills. It is a relatively simple procedure to mark oiled birds and monitor their recovery on beach surveys. Information should be collected simultaneously on the at-sea distribution of birds and the trajectory of the oil. If properly executed, such experiments could provide relatively inexpensive and accurate estimates of total seabird mortality from individual oil spills and help in assessing mortality from spills where such experiments are not possible.

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