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MORTALITY OF SEA OTTERS IN PRINCE WILLIAM SOUND FOLLOWING THE *EXXON VALDEZ* OIL SPILL

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Abstract

This paper presents an estimate of the total number of sea otters that died as a direct consequence of the oil spill that occurred when the T/V *Exxon Valdez* grounded in Prince William Sound, Alaska on 24 March 1989. We compared sea otter counts conducted from small boats throughout the Sound during the summers of 1984 and 1985 to counts made after the spill during the summer of 1989. We used ratio estimators, corrected for sighting probability, to calculate otter densities and population estimates for portions of the Sound affected by the oil spill. We estimated the otter population in the portion of Prince William Sound affected by the oil was 6,546 at the time of the spill and that the post-spill population in the summer of 1989 was 3,898, yielding a loss estimate of approximately 2,650. Bootstrapping techniques were used to approximate confidence limits on the loss estimate of about 500–5,000 otters. The wide confidence limits are a result of the complex scheme required to estimate losses and limitations of the data. Despite the uncertainty of the loss estimate it is clear that a significant fraction of the otters in the spill zone survived. We observed otters persisting in relatively clean embayments throughout the oil spill zone suggesting that the highly convoluted coastline of Prince William Sound produced refuges that allowed some sea otters in the oil spill area to survive.

Key words: bootstrapping, boat surveys, census techniques, sighting probabilities, mortality, population growth, contaminants, *Enhydra lutris*, impacts of oil spill, carcass recovery rates, Prince William Sound, Alaska.

There is general agreement that the sea otter (*Enhydra lutris*) is one of the most vulnerable of marine mammals to the effects of oil spills (Geraci and

Williams 1990, Ralls and Siniff 1990). Otters depend on a high metabolism and air trapped in their pelage for insulation and thus are extremely vulnerable to matting of the fur by oil (Siniff *et al.* 1982, Geraci and Williams 1990). The T/V *Exxon Valdez* oil spill in Prince William Sound, Alaska, is the first instance in which a sizable population of sea otters has been exposed to a large-scale oil spill, so the results are of considerable importance in understanding the consequences of such events.

The spill occurred when the T/V *Exxon Valdez* went aground on Bligh Reef in Prince William Sound on 24 March 1989, releasing approximately 11 million gallons of crude oil. A major effort was mounted to clean up the spill and to rescue birds and sea otters from the affected area, as well as to recover carcasses of those dying in the area. We estimate the total number of sea otters in Prince William Sound that died as an immediate consequence of the oil spill, and suggest a minimum possible recovery time for the population. The basic data are counts of sea otters made in Prince William Sound 4–5 yr before the spill (Irons *et al.* 1988), and a similar survey conducted several months after the spill.

Survey Area

Prince William Sound is a large estuarine system about 100 km southeast of Anchorage, Alaska. The shoreline is highly convoluted, and there are many islands and a large area of open water. The Sound is bounded to the southeast by two large islands, Montague and Hinchinbrook (Fig. 1). The oil spill originated in the northeastern portion of the area, and the oil moved southwest towards Kenai Peninsula and Kodiak Island.

Data and Data Collection Procedures

Boat surveys—During June through August of 1984 and 1985 the entire shoreline of Prince William Sound was surveyed for sea otters and marine birds (Irons *et al.* 1988). Small power boats were used to make visual counts of marine birds and sea otters along a series of transects that paralleled the coastline at a distance of 100 m from shore. All sea otters seen inshore of the boat were counted, along with those seen in a 100-m strip on the offshore side of the boat. The transects were convenient segments of the length of the course of the boat, often being circumnavigations of small islands or points. Two summers were required to cover the entire Sound. Seventy-six percent of the 1984 counts were in the oil spill area, whereas in 1985, 82% of the counts were in portions of the Sound that were largely unaffected by oil (Fig. 1).

In the aftermath of the oil spill a 25% random sample of the transects covered in 1984 and 1985 was resurveyed using techniques as close as possible to those of the earlier surveys (Burn 1990). Additional surveys were also conducted in 1989 to cover offshore areas, defined as all areas outside the 200 m shoreline strip. These open water areas were sampled by drawing a 25% random sample of 5-minute by 5-minute blocks of latitude and longitude. Some of the blocks

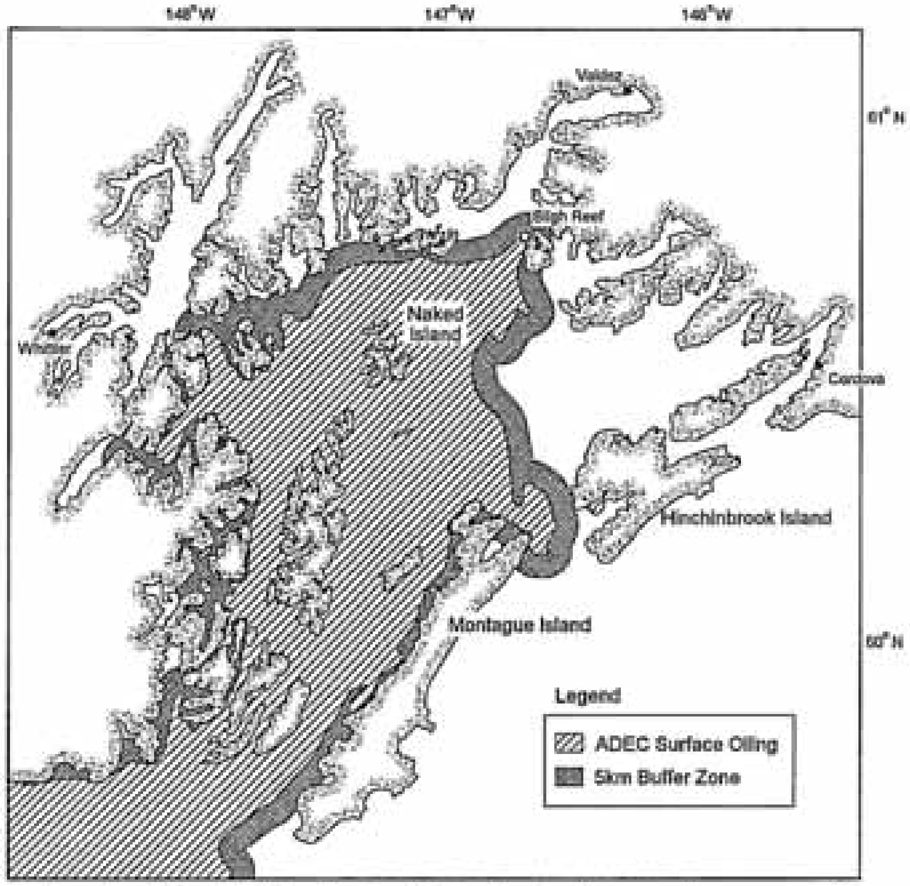

Figure 1. Prince William Sound, Alaska, showing the approximate extent of contamination resulting from the *Exxon Valdez* oil spill. (ADEC: Alaska Department of Environmental Conservation)

selected impinged on the shoreline and were labelled as coastal, while others fell entirely in open water areas and were designated as pelagic. Each block was subsampled by surveying two systematically placed 200-m wide strips running the length of the block.

The 1989 survey thus contained three strata. One was a 200-m wide strip along the shoreline, sampled as a 25% random sample of the 1984 and 1985 transects, and thus covered close to 25% of the actual shoreline area of the Sound. A second stratum was comprised of the pelagic blocks, selected as a 25% random sample of open water areas, but, in consequence of the subsampling, actually covered about 2.6% of the water area. The third stratum, coastal blocks, was sampled at essentially the same intensity but the blocks were individually of variable size, depending on how each block impinged on the coastline. The actual sampling intensity was about 1.9% of the area designated as coastal. Only the shoreline stratum was surveyed in June 1989 while all three strata were sampled during replicate surveys conducted in July and August. With the exception of minor discrepancies due to weather and logistic constraints, the same transects were counted during the three replicate surveys.

Ground-truth study—An auxiliary study was conducted during the summer of 1990 to estimate the proportion of the otters that were not detected during boat surveys (Udevitz *et al.* 1990). This ground-truth study was patterned after similar work in California (Geibel and Miller 1984) and was staffed by biologists with experience in those earlier studies. Shoreline observers were placed at sites in advance of the arrival of the survey boats and counted otters in the survey strip. Results were then contrasted with those from the boat survey to obtain corrections for sea otters missed in the main survey. Two different sources of error were noted. One was that some otters immediately left the shoreline strip when they detected the approaching boat, and the other included otters that remained on the transect but were not seen by the boat-based observers. Results of the ground-truth study were used in the estimation of total loss to correct for otters not sighted by the boat survey observers.

Oiling classification—The oiling classification presented in this paper (Fig. 1) was based on Alaska Department of Environmental Conservation (ADEC) overflight data collected during the spill period. The aerial observations were used to create a geographic information system coverage depicting the cumulative distribution of the oil. Since sea otters are highly mobile animals, it is possible that otters inhabiting areas outside the pathway of the oil could have moved into the area of the slick and become oiled. For this reason, an arbitrary buffer zone of 5 km was added to the ADEC overflight data to represent an area within which otters might have been affected by oil. Shoreline transects, and nearshore and offshore blocks with any area located within 5 km of the oil were, therefore, classified as oiled. The inclusion of the buffer may result in a more conservative estimate of losses because it may include areas where otters were not affected by oil.

Estimating Total Losses

One of the complications in loss estimations is that the 1984 and 1985 surveys covered only the shoreline area and did not provide information on the number of sea otters in open water areas at that time. Because sizable numbers of otters were counted in both the 1984 and 1985 surveys and on the shoreline transects of the 1989 survey, the data provide a reasonably precise estimate of the degree of change between 1984–1985 and 1989. However, evidence from a variety of sources (described below) indicated that the population was increasing during the period in question, and thus would have been larger at the time of the oil spill than it was in 1984–1985. We thus needed to adjust for growth of the population from 1984–1985 to 1989.

The difference between the shoreline density of otters in 1989 immediately after the oil spill, and the shoreline density of otters in 1984–1985, adjusted for population growth, provided an estimate of the relative loss in the population that could be attributed to the oil spill. However, in order to calculate the total number of otters lost in the oil spill, an estimate of the total population size was also needed. The only data adequate to estimate total population size are those from 1989, when the entire Prince William Sound area was sampled.

Estimating the number of otters lost from the Prince William Sound population required four steps. First, a post-spill population estimate was obtained for the oil spill area, using data from the 1989 boat surveys and the ground-truthing study conducted in 1990. Secondly, a 1984–1985 population estimate for the oil spill area was calculated using shoreline otter densities obtained from the 1984–1985 and 1989 boat surveys and the 1989 post-spill population estimate. Thirdly, population growth from 1984–1985 to 1989 was estimated using shoreline otter densities from portions of Prince William Sound outside the oil spill area. This growth rate was then used to project the 1984–1985 population to the level expected in the oil spill area in 1989. The final step was to subtract the 1989 population estimate in the oil spill area from the population expected to be there had an oil spill not occurred, giving an estimate of the total loss due to the oil spill. Details of the necessary calculations appear in the following sections.

1989 population estimate in oiled area—A population estimate for 1989 was obtained by the usual stratified random sampling approaches. One complication is that the coastal blocks vary in area actually searched. A convenient way to deal with this difficulty is to use ratio estimators. All of the shoreline transects were counted three times (in June, July, and August) of 1989, but the coastal and pelagic blocks were surveyed only in July and August. We thus used the 3 month average counts for shoreline data, and the average of the July and August counts for the coastal and pelagic strata.

Cochran (1977) gives the ratio estimator as

$$\hat{Y}_R = \frac{\Sigma\, y_i}{\Sigma\, x_i} X$$

where $\hat{Y}_R$ represents the estimate of total number of otters in a given stratum, y_i is the count of otters on the ith transect, and x_i is the area of the ith transect, while X is the total area of all shoreline transects. Since transects were all of the same width (200 m), one might equally well use x as length of an individual transect and X as total length of available transects. Such an arrangement is, in fact, conceptually preferable as it permits following Cochran's equations exactly. We thus start out by considering the shoreline stratum first. The variance estimate used here is (Cochran 1977, p. 155, equation 6.10):

$$v(\hat{Y}_R) = \frac{N^2(1-f)}{n(n-1)}(\Sigma\, y_i^2 + \hat{R}^2\, \Sigma\, x_i^2 - 2\hat{R}\, \Sigma\, y_i x_i) \qquad (1)$$

where N is the total number of shoreline transects available, n is the number sampled, drawn at random from N, and $f = n/N$ is the sampling fraction, *i.e.*, the proportion of transects actually counted. For the shoreline stratum this was about 25%. It may be noted that $1 - f$ is the finite population correction, which is important if a substantial fraction of the area is sampled. $R = \Sigma\, y_i/$

Table 1. Post-spill estimates of the sea otter population in the area of Prince William Sound affected by the *Exxon Valdez* oil spill. Estimates for each of the three strata were obtained using ratio estimation procedures and the average sea otter counts obtained during independent boat surveys conducted in the summer of 1989. Area was measured in km^2 and density as the number of otters per km^2.

Stratum	Total area	Area sampled	No. transects	Density $\hat{R}$	Pop. est. $\hat{Y}_R$	Standard error
Shoreline	444.8	125.4	118	3.502	1,557	184
Coastal	2,546.8	44.1	21[a]	0.204	520	160
Pelagic	2,791.9	70.7	19[a]	0.226	632	379
Total	5,783.5				2,709	451

[a] Number of sample blocks with two systematically placed transects within each block.

Σx_i, the estimated ratio, and is, in this case, a density of otters (per km^2 if areas are used, per km if lengths are used as x).

A difficulty arises in the variance estimation in that the open water areas were sampled with a different arrangement, as previously noted. The sampling units are 5-minute by 5-minute blocks with two 200-m-wide transects systematically located within each block. Hence, only a small fraction (8 or 9%) of a given block was actually surveyed for otter abundance. In sample survey terminology, the open water strata were surveyed by using cluster sampling with two systematically located subsampling units in each sample unit (block). Although 25% of the available blocks were included in the sample, the actual area searched for otters was only about 2.5% of the total open water area. A different method for calculating variance might thus be used for the pelagic stratum as discussed by Cochran (1977) in chapters on cluster sampling. However, the area searched in the coastal stratum varied from block to block, depending on how the particular block intercepted the coastline. Hence, calculation of variances becomes more complicated for the coastal blocks.

While schemes might be devised to calculate variances for coastal blocks, any complex approach will likely be unsatisfactory due to the high fraction of transects on which no otters were counted (over 70% for individual months). Hence, we have used the variance formula given above for all strata, with a small modification, obtained by rearranging the multiplier of the quantity in parenthesis on the right:

$$\frac{N^2(1-f)}{n(n-1)} = \frac{nN^2(1-f)}{n^2(n-1)} = \frac{n(1-f)}{(n-1)f^2}$$

recalling that $f = n/N$. With this change, we now estimate the sampling fraction, f, as the proportion of the total area actually surveyed. Results of these calculations for the oil spill area are presented in Table 1.

The ratio estimates given in Table 1 are for uncorrected counts from the boat surveys. The ground truth survey yielded an estimate of 69.5% of the otters present on transect units were actually tallied in the boat surveys (Udevitz *et al.* 1990). The calculated total can be corrected by dividing the population estimate by the proportion of otters counted, giving a corrected 1989 population estimate for the oil spill area of 3,898 (2,709/0.695).

1984–1985 population estimate in oiled area—To obtain a 1984–1985 population estimate in the oiled area, we adjusted the estimated 1989 population in the oiled area by the ratio of the shoreline density in the same area in 1984–1985 to the shoreline density in 1989. The 1984–1985 population estimate was calculated as:

$$\hat{N}_{1984-1985} = \frac{d_{1984-1985}}{d_{1989}} \hat{N}_{1989,\text{post-spill}} \qquad (2)$$

where $d_{1984-1985}$ and d_{1989} represent the density estimates for the shoreline transects counted by Irons *et al.* (1988) in 1984–1985 and Burn (1990) in 1989 and $\hat{N}_{1989,\text{post-spill}}$ is the corrected 1989 post-spill population estimate developed in the previous section. Irons *et al.* (1988) surveyed 95% of the shoreline transect area within the oil spill area (420.4 km^2) and counted 2,194 otters for a density estimate of 5.218 otters/km^2. Thus the 1984–1985 population estimate in the oiled area was calculated as:

$$5.218/3.502(3{,}898) = 5{,}808.$$

An assumption inherent in this calculation is that the density of otters offshore (>200 m) changed in direct proportion to the density of otters within 200 m of the shoreline surveyed in 1984 and in 1989.

Projecting 1984–1985 population in oiled area to 1989—Projecting the 1984–1985 population estimate for the oiled area to 1989 required an estimate of the trend in the population during this period. Since the 1950s the Prince William Sound population has been growing and expanding its range from the southern portion of the Sound northward (Pitcher 1975). Estes (1990) suggests expanding sea otter populations may increase at annual rates of 17–20%. Such high rates of growth would not be expected in Prince William Sound since most of the region was recolonized by otters by 1974 (Pitcher 1975) with the last area of suitable habitat along the extreme northeastern edge of the Sound reoccupied by 1980 (Garshelis and Garshelis 1984). There are no direct estimates of trends in sea otter numbers during the period from 1984 to 1989, therefore we used the change in shoreline otter densities calculated from 1984–1985 and 1989 boat surveys in areas outside the spill zone (Fig. 1). Since most portions of both the oiled and unoiled areas of Prince William Sound had been occupied for at least a decade prior to the boat surveys in 1984–1985, we assumed population changes in the unoiled area would be representative of those in the oiled areas as well.

Irons *et al.* (1988) counted 1,761 otters on 386.7 km^2 of shoreline transects outside the oiled area for a density estimate of 4.533 otters/km^2. Burn (1990) surveyed 86.8 km^2 of shoreline transects outside the oil spill area during the summer of 1989, counting a mean of 445.3 otters for a density estimate of 5.130 otters/km^2. Thus we assume that the population in the oil spill area increased approximately 12.7% between 1984–1985 and 1989, indicating a modest 2% annual growth rate. Adjusting the 1984–1985 population estimate to account for this growth yields a projected 1989 population estimate of 6,546 (5,808 × 1.127) in the oiled area.

Estimate of otters lost from population of oiled area—In the previous section we developed an estimate of the number of sea otters that should have been present in the oiled area during the summer of 1989 had the oil spill not occurred. An estimate of the number of sea otters lost due to the oil spill can then be obtained by simply subtracting the estimated actual 1989 population from the projected population estimate, yielding a loss estimate of 6,546 − 3,898 = 2,648. This estimate was developed through a series of calculations given in the preceding sections as individual steps. However, these can be combined into a single algebraic equation:

$$\text{Loss estimate} = \frac{\hat{N}_{1989}}{\hat{\beta}}\left\{\left[\frac{d_{1984-1985\,\text{oiled}}}{d_{1989\,\text{oiled}}}\right]\left[\frac{d_{1989\,\text{non-oil}}}{d_{1984-1985\,\text{non-oil}}}\right]-1\right\} \quad (3)$$

where $\hat{N}_{1989}$ represents the number of sea otters present in the oil spill area during the summer of 1989, $\hat{p}$ represents the proportion of otters present on transect lines that are actually seen by the survey crews, $d_{1984-1985}$ and d_{1989} represent the densities of sea otters on shoreline transects in areas affected and not affected by the oil spill that were surveyed in 1984–1985 and 1989, respectively.

Bootstrapping for Confidence Limits

Due to the complicated form of the several ratios used in the loss calculations above, direct variance estimates on the number lost are difficult to obtain. Consequently, we have approximated confidence limits on the loss estimate by using the bootstrapping technique (Efron 1982). As used here, bootstrapping consists of taking N random samples with replacement from the data and constructing N estimates of a quantity such as the loss estimate of Equation (3). The frequency distribution of these N results then provides approximate confidence limits for the estimate of main interest. Sampling with replacement means that the same item can be drawn more than once in a given sample. Each of the separate data sets may consist of, say, n_i items, and the samples from each such set will consist of exactly n_i random draws with replacement.

Equation (3) requires six different estimates, but one of these ($\hat{N}_{1989}$) is based on a stratified random sample with three strata (shoreline, coastal, and pelagic), so there are eight different data sets in all. The population estimate for the oiled area was based on a sample of 118 shoreline transects, 21 in the coastal, and 19 in the pelagic stratum (these two strata were counted only in July and August, so each entry is the average of two counts). The proportion seen ($\hat{p}$) was estimated from a sample of 21 ground truth checks, each including the number of otters seen from the survey boat and the number identified by the shoreline observers just before the boat reached the ground truth site.

The two density estimates in the oiled area were based on 426 transects (1984–1985) and 118 transects (1989). The 1989 counts are based on the same transects as the shoreline stratum above, but are now based on the average of June, July and August counts, whereas only the July and August counts were used in the population estimate because only July and August counts were made in the open water areas. The counts in the non-oiled area were based on 296 transects (1984–1985) and 69 transects (1989). Each calculation of a loss estimate required sampling eight data sets, and completing the calculations for the estimates needed for Equation (3).

The required data were assembled in spreadsheet software and exported to ASCII files for a BASIC language program that performed the bootstrapping. Verification was accomplished by another BASIC program that calculated means from the ASCII files that could be compared with the same values calculated in the spreadsheets. Also, in nearly all calculations the mean of the bootstrap samples gave essentially the same result as the above two sources.

Results of bootstrapping—A frequency distribution (Fig. 2) of the results of $N = 2{,}000$ runs of the bootstrap program yields a skewed distribution, as would

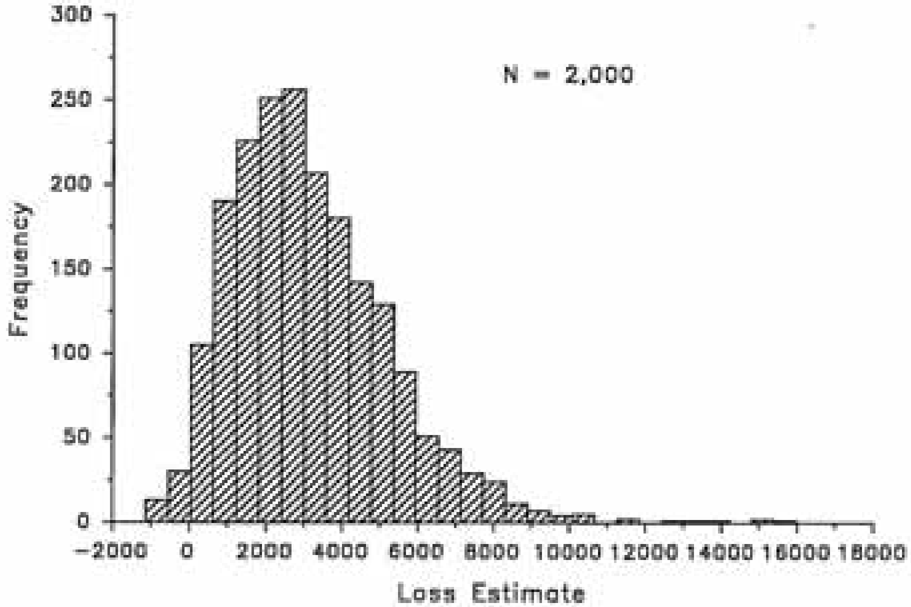

Figure 2. Frequency distribution of bootstrap estimates of number of sea otters lost in Prince William Sound. A lower limit of about 500 is established by the number of carcasses of sea otters recovered in shoreline searches. Upper limits of 5,800 and 6,900 cut off 10% and 5% of the upper tail of the frequency distribution.

be expected when ratios are involved. Standard errors calculated in the program were about 2,000 otters on the loss estimate of 2,650 sea otters (since the distribution is asymmetric, confidence limits from the frequency distribution may be more satisfactory). If we assume, as seems reasonable, that the population in the oiled area did not decrease from 1984 to 1989, and did not increase more than 10% per year, then these limits can be inserted in the bootstrap program to bound the variability of that ratio component. Inserting such bounds gives an appreciably smaller standard error for the loss estimate, *i.e.*, about 1,800.

Another prospect for obtaining somewhat narrower confidence limits depends on recent experience with the bootstrapping technique. Rao and Wu (1988, p. 234) suggest using bootstrap t-intervals instead of the percentile limits given above. Obtaining such limits requires "double-bootstrapping" in which each individual bootstrap sample is submitted to the bootstrap process in order to obtain a variance estimate for each of the original bootstrap samples. With these variances available, one can then construct a t-statistic for each bootstrap sample:

$$t_i = \frac{\hat{\theta}_{bi} - \hat{\theta}}{s_i}$$

where $\hat{\theta}_{bi}$ is the loss estimate from a given bootstrap sample, $\hat{\theta}$ is the loss estimate based on the original data set, and s_i is the square root of the variance estimate obtained by bootstrapping the bootstrap sample. A frequency distribution of these *t*-statistics is then used to select a value at the chosen alpha level of significance.

Using the restriction mentioned above (growth from 1984–1985 to 1989 restricted to the range of 0 to 10% per year) the *t*-statistic with bootstrap samples of 1,000 gave an upper 5% confidence limit of about 4,600 otters, while using the *t*-statistic in unrestricted bootstrapping yielded upper limits of about 5,300 otters. We thus propose that confidence limits of about 500–5,000 may be appropriate for the loss of about 2,650 sea otters from Prince William Sound, with the lower limit established by the known number of carcasses of otters picked up after the spill.

An approximate notion of the contribution of the several quantities in Equation (3) to overall variance can be constructed as follows. A variance estimate from Equation (1) is available from Cochran (1977) and Udevitz *et al.* (1990) provide a variance estimate for p. A variance for the product of the two ratios was approximated by bootstrapping. Writing Equation (3) as:

$$LOSS = NR/p \tag{4}$$

the delta method (Seber 1982, p. 7) can be used to obtain an approximate coefficient of variation as:

$$CV^2(LOSS) = CV^2(N) + CV^2(p) + CV^2(R). \tag{5}$$

Covariance terms are neglected here. The calculations give

$$CV^2(LOSS) = 0.17 + 0.08 + 0.634 = 0.88.$$

For comparison, the bootstrap calculations gave a coefficient of variation of 0.72. We thus see that roughly 70% of the variability is due to the product of the two ratios.

Recovery Time

Many factors may affect the recovery of the Prince William Sound sea otter population, including any direct effects of residual hydrocarbons in the Sound, and the various possible effects on the food base (Neff 1990). Most such factors apparently are not well-documented. As indicated above, we estimate about half of the otters in the oil spill area were lost. Replacements may come from population growth within the oil spill area or from the immediately adjacent areas outside the oil spill area. Because we have little basis for judging relative contributions from these several sources, it seems advisable to make any projections into the future on the basis of the Prince William Sound population as a whole, rather than trying to focus on the oil spill area only.

The present Prince William Sound sea otter population is believed to have originated from one or more remnant populations that survived the exploitation era in the southern portions of the Sound and perhaps at Kayak Island (Lensink 1962, Rotterman and Simon-Jackson 1988). By about 1980, the area covered by the boat surveys had largely been repopulated (Pitcher 1975, Garshelis and Garshelis 1984). Two earlier surveys provide approximate population estimates for the entire Prince William Sound region populated by otters. In 1959, Lensink (1962) counted 564 otters in aerial surveys, and estimated the total population as being between 825 and 1,275 otters. In 1973 Pitcher (1975) conducted helicopter surveys along the shoreline, and counted 2,015 otters, estimating a total population of 5,000. We have used the counts of Irons *et al.* (1988) and Burn (1990) to obtain two additional population estimates for the region covered by the boat surveys in 1984–1985 and 1989, respectively. The boat surveys, however, did not include an important area at the northeastern edge of the Sound in the vicinity of Cordova (Orca Inlet, Hawkins Cutoff, and the Copper River Delta area). From data provided by Garshelis and Garshelis (1984) and aerial surveys conducted by Simon-Jackson (1986, 1987) we estimate that roughly 1,000 otters were in this area at the time of the 1984–1985 surveys. In June and August of 1988 Monnett and Rotterman (1989) conducted two similar aerial surveys and counted 3,473 and 3,229 otters. With these data, we can expand our population estimates for 1984–1985 and 1989 to account for the entire Prince William Sound population, and construct an approximate growth curve for the area (Fig. 3). A log-linear regression on the four points suggests a rate of growth of approximately 9% per year. This is considerably higher than the 2% annual growth rate estimated using the change in shoreline otter densities calculated from the 1984–1985 and 1989 boat survey data. This difference is due to the rapid increase in otter numbers in the Orca Inlet and Hawkins Cutoff areas, which were not sampled in the boat surveys.

A very simple approximation of a minimum recovery time can be obtained by noting that the overall loss (approximately 2,650 otters) would require approximately three years to replace at the rate implied by the apparent rate of growth between 1959 and 1989 (Fig. 3). However, the 1990 and 1991 boat surveys indicate that no population growth occurred in those two years in the area covered by the surveys, and telemetry studies conducted during this period documented extremely low weanling survival (Burn, Rotterman and Monnett, unpublished data). Given these data, a more conservative estimate of recovery time would appear to be at least five years, if recovery is defined as the time required to reach the population level existing at the time of the oil spill. With the limited data available on the impact of the oil spill on the sea otter food base, we cannot assume that the population is undergoing rapid recovery.

Discussion

An unfortunate consequence of the somewhat complex scheme required to estimate the number of sea otters lost in Prince William Sound from the T/V *Exxon Valdez* oil spill is that confidence limits on the final loss estimate are larger than desired. A study involving marking of carcasses and subsequent recovery in shoreline searches would likely have produced estimates with much smaller confidence limits. A small-scale study of this kind was conducted near Kodiak Island during the oil spill by DeGange *et al.* (personal communication), who reported 5 of 25 marked sea otter carcasses were retrieved, giving a

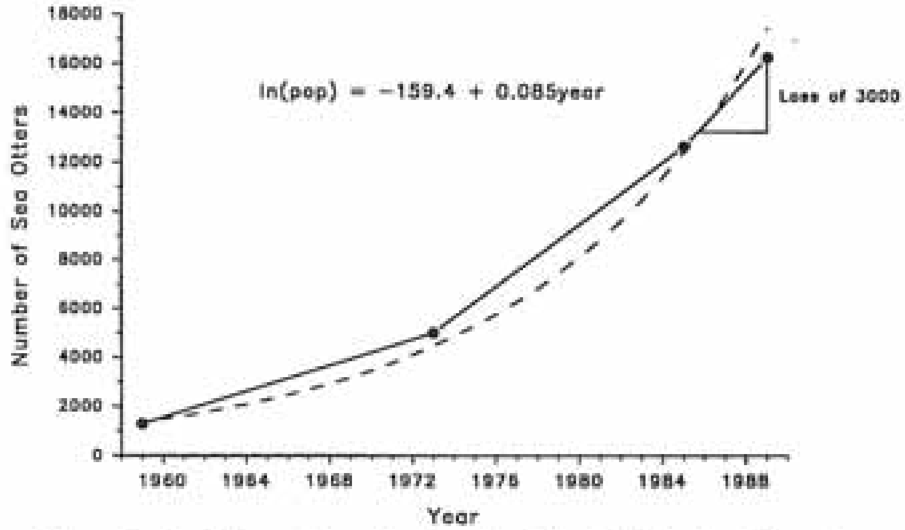

Figure 3. Population estimates for the entire Prince William Sound area. Arrows show the likely effect of the oil spill loss on population size. The dashed line is the fitted geometric growth rate.

proportion recovered as $p = 5/25 = 0.20$ (DeGange *et al.*, personal communication). An independent estimate of the proportion of carcasses recovered in Prince William Sound can be calculated by using the loss estimate of 2,648 developed from the boat survey data. A total of 511 sea otter carcasses were recovered in Prince William Sound that were classified as oil spill mortalities (Bayha and Kormendy 1990), yielding an estimate of the proportion recovered as $511/2{,}648 = 0.19$, nearly the same as the estimate derived from the Kodiak Island data. Applying the 20% recovery rate to the total number of carcasses recovered that were classified as oil spill mortalities would result in a loss estimate of 4,600 otters for the entire region affected by the spill. The success of a carcass recovery study to estimate the number of otters killed by an oil spill, however, depends on mounting a very intensive carcass recovery effort, as was done following the T/V *Exxon Valdez* oil spill. In other circumstances, such an effort might not be possible.

The analysis of sea otter losses presented in this paper was complicated by the fact that the pre-spill survey was conducted several years before the oil spill occurred, raising the issue of possible changes in the population between the pre-and the post-spill surveys. Estes (1991) suggests a comprehensive survey should have been conducted immediately after the spill but before the oil dispersed throughout the Sound and the Gulf of Alaska. Given the logistics, costs, and pressures placed on natural resource agencies during such emergencies this recommendation would have been extremely difficult to implement. An alternative approach would be to conduct comprehensive surveys of otter populations vulnerable to oil spills at 2- to 3-yr intervals as established populations would not be expected to change dramatically over this short time period. If a recent pre-spill population estimate is not available, we believe plans for a mark-and-recapture survey of carcasses should be part of spill response activities. However, the success of such a survey will depend on marking a representative sample of carcasses, which may be difficult to achieve as outboard motors can be quickly destroyed when operated in heavy oil where many of the carcasses are found. The recapture phase will depend on examining a sizable number of carcasses for marks. About 500 carcasses were examined in the course of the study in Prince William Sound, but this resulted from a very large effort. Whether such an effort would be mounted in future studies depends very much on a decision outside the scope of the present paper, *i.e.*, whether to attempt to "salvage" living otters exposed to oil.

In the immediate aftermath of an oil spill, it will not be possible to predict values needed for determination of sample sizes as suggested for the usual marking experiments (described by Seber 1982: chapter 3). Instead, a decision as to the proportion of carcasses to be marked very likely will have to be made. Seber (1982, p. 566) suggests using an estimated coefficient of variation which can be written as:

$$CV^2 = \frac{N - m}{nM} = \frac{1 - p}{np}$$

where N is the size of the population of dead otters, M is the number of carcasses marked, and n is the number later examined for marks. Inasmuch as it will be virtually impossible to predict N, we suggest using the right-hand expression where $p = M/N$, the proportion marked. A decision can then be made as to the proportion of carcasses to mark, and values of n calculated for various choices of the coefficient of variation. If approximately 95% confidence limits of about ± 50% of the total loss are sought and 5% of the carcasses encountered are marked, then the sample to be later examined for marks would be calculated as:

$$n = \frac{0.95}{(0.25)^2 0.05} = 300$$

Another desirable feature would be to use radiotelemetry both to follow the fate of carcasses and to monitor the status of live otters in areas likely to be affected by the subsequent movement of spilled oil. The chief problem with such a scheme will likely be catching otters for attachment of transmitters before the oil spill reaches them. If this can be accomplished, the use of radiotelemetry has the advantage that an estimate of survival rates and some important auxiliary information can be obtained concerning behavioral responses to oil and the effectiveness of a mark-recapture scheme as described above. For example, it is possible that some carcasses may sink and never be available for recovery. One could also investigate the prospect by attaching transmitters to the carcasses.

Clearly the oil spill had a significant effect on the sea otter population of Prince William Sound. It is, however, also important to note that perhaps 70–

80% of the population survived the spill. Much of the surviving population was simply outside of the spill zone. Very likely the shoreline transects give the best indication of the affected area as it concerns sea otters. About 2,544 km of shoreline were classified as affected by the oil, out of 5,138 km of shoreline considered. Thus, about 50% of the total sea otter habitat was affected, while our estimates suggest that about 40% of the sea otter population in the oil spill area was lost.

Some insights into the circumstances in which otters in the spill zone may have survived are suggested by the senior author's observations when conducting intensive aerial surveys over the spill area during a two-week period just after the spill occurred. During these flights the author noted that even in areas such as Naked Island, which was the first major land mass to be heavily oiled, otters were present in small bays and coves that appeared to be relatively free of heavy oil. Repeated flights over these areas revealed that otters persisted in the "clean" coves for several weeks despite the fact that the surrounding coastline and water surface were heavily oiled. These apparent refuges were scattered throughout the oil spill area and appeared to be most common in areas that were protected from the prevailing northeast winds that pushed the oil through the Sound.

In contrast, the Prince of Wales Passage in the southwestern corner of the Sound is a relatively straight and narrow passage oriented with the prevailing winds. When the author surveyed the passage on 1 April 1989, the oil had just reached this area and all 26 otters observed in the passage were in heavy oil. The only area not heavily oiled was a small bay along the northeastern edge of the passage which contained an additional 23 otters. Biologists visited this area several days later and reported that most of the otters in the bay were oiled to some degree, suggesting that otters in this apparent refuge were still exposed to oil. These observations suggest that the highly convoluted and complex coastline of Prince William Sound may have been a major factor that allowed a relatively large proportion of the sea otters in the oil spill area to survive.

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