Exxon Valdez Oil Spill
State/Federal Natural Resource Damage Assessment Final Report

The Effects of the *Exxon Valdez* Oil Spill on Black Oystercatchers Breeding in Prince William Sound, Alaska

Bird Study Number 12
Restoration Study Number 17
Final Report

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Study History: Bird Study 12 was initiated as a damage assessment study in 1989. Work on the assessment of continued injury was conducted in 1991 as Restoration Project 17. Interim reports were made by B. E. Sharp in 1989 (Black oystercatchers in Prince William Sound: Oil spill effects on reproduction and behavior) and by B. A. Andres in 1991 (Feeding ecology and reproductive success of black oystercatchers in Prince William Sound).

Abstract: Black oystercatchers (*Haematopus bachmani*) were studied in central Prince William Sound, Alaska, to determine the effects that the *Exxon Valdez* oil spill had on their population, reproductive biology, and behavioral ecology. Estimates of direct mortality of black oystercatchers varied widely among the methods used to assess losses and ranged from 4% to 57% of the population inhabiting the spill zone; mortality probably did not exceed 20% of the population. The breeding activity of many pairs, however, was disrupted along oiled shorelines in Prince William Sound. Consequently, hatching success was reduced ($P \leq 0.001$) on Green Island in 1989. Sublethal effects of the spill on black oystercatchers were evident in 1991. Chicks raised at oiled nest sites gained weight slower ($P \leq 0.034$) than chicks raised at unoiled nest sites, despite that chicks at oiled nest sites consumed more food ($P \leq 0.025$) than chicks at unoiled nest sites. Although the black oystercatcher population appears to be recovering in some areas of the Sound, delayed reproduction in the species precludes determination of the total effect of the spill on the population until at least 1994. Hydrocarbon concentrations in some oiled mussel beds in Prince William Sound remained high into 1991 and might provide a chronic source of exposure of black oystercatchers to oil.

Key Words: Alaska, behavior, black oystercatcher, chick growth, crude oil, foraging, *Haematopus bachmani*, reproductive success.

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EXECUTIVE SUMMARY

Black oystercatchers (*Haematopus bachmani*) were studied in central Prince William Sound, Alaska, to determine the effects that the *Exxon Valdez* oil spill had on their population, reproductive biology, and behavioral ecology.

Estimates of direct mortality of black oystercatchers varied widely among the methods used to assess losses and ranged from 4% to 57% of the population inhabiting the spill zone. Rapid reoccupation of Green Island, a heavily oiled site, by oystercatchers in post-spill years indicated that many breeding pairs were displaced by oil spill disturbances and mortality probably did not exceed 20% of the population. The breeding activity of many pairs, however, was disrupted along oiled shorelines in Prince William Sound (≥39% of the pairs on Green Island in 1989 did not maintain nests into early June). Consequently, hatching success was reduced ($P \leq 0.001$) on Green Island in 1989. For nests that hatched young, chicks were lost at a greater rate ($P \leq 0.079$) from nests at heavily or moderately oiled shorelines than from nests at unoiled shorelines.

Cleanup activities also disrupted breeding birds on Green Island. In 1990, survival of chicks in nests that were disturbed by cleanup activities was lower ($P \leq 0.005$) than survival of chicks in nests that were undisturbed.

Sublethal effects of the spill on black oystercatchers were evident. Female condition and chick growth were possibly impaired by the ingestion of oil. The relative difference between the volume of the largest and smallest egg of 3-egg clutches laid by females nesting on oiled shorelines in 1989 was greater ($P \leq 0.045$) than the relative difference of eggs laid by females nesting on unoiled shorelines. Chicks raised at oiled nest sites gained weight slower ($P \leq 0.034$) than chicks raised at unoiled nest sites, despite that chicks at oiled nest sites consumed more food ($P \leq 0.025$) than chicks at unoiled nest sites.

Contaminated food was the most likely route for exposure of black oystercatchers to oil. Blue mussels (*Mytilus trossulus*) collected on oiled shorelines in 1989 had higher concentrations of petroleum hydrocarbons and higher mortality rates ($P \leq 0.02$) than mussels collected on unoiled shorelines. Ingestion rates of oystercatchers feeding on oiled substrates were lower ($P \leq 0.001$) than ingestion rates of birds feeding on unoiled substrates.

Although the black oystercatcher population appears to be recovering in some areas of the Sound, delayed reproductive in the species precludes determination of the total effect of the spill on the population until at least 1994. Hydrocarbon concentrations in some oiled mussel beds in Prince William Sound remained high into 1991 and might provide a chronic source of exposure of black oystercatchers to oil.

INTRODUCTION

On March 24, 1989, the *T/V Exxon Valdez* ran aground in northern Prince William Sound, Alaska, and released 42 million L of Prudhoe Bay crude oil into the marine environment. Approximately 40% (16.7 million L) of the spilled oil was deposited along 563 km of Prince William Sound's shorelines (Galt and Payton 1990). Oiling was heaviest on islands in central Prince William Sound. Because oil that contacts shorelines persists longer than oil that remains suspended in the water column (National Research Council 1985, Galt and Payton 1990), species inhabiting shorelines, such as the black oystercatcher (*Haematopus bachmani*), are particularly vulnerable to direct and indirect consequences of oil that washes ashore.

Black oystercatchers are completely dependent upon marine shorelines for their life's requirements. Oystercatchers nest on supratidal boulders and gravel beaches and forage in the intertidal zone. Diets of adults and chicks consist of benthic and epibenthic molluscs (Webster 1941), mainly mussels (*Mytilus*) and limpets (*Techtura* and *Lottia*). Of all marine molluscs, bivalves most readily accumulate petroleum hydrocarbons (National Resource Council 1985). Therefore, black oystercatchers had the potential of being directly, through physical contact, and indirectly, through ingestion, exposed to oil spilled from the *Exxon Valdez*.

Oil contamination affects birds in a variety of ways. Contact with crude oils or oil-dispersant mixtures reduces the heat retention ability of a bird's plumage and eventually leads to death from hypothermia (Hartung 1967, Jenssen and Ekker 1991). Oil adhering to the plumage or feet of an incubating bird is readily transferred to eggs and kills embryos (Lewis and Malecki 1984). Ingestion of significant amounts of oil, by either consuming contaminated prey or preening contaminated feathers (Hartung 1963), reduces the condition of the individual. Numerous studies have documented deleterious, sub-acute effects of oil ingestion on avian reproduction. Petroleum-dosed female mallards (*Anas platyrhynchos*) produced fewer eggs (Coon and Dieter 1981), hatched fewer eggs (Szaro and Albers 1978), and changed incubation behavior (Cavanaugh et al. 1983). Wedge-tailed shearwaters (*Puffinus pacificus*) dosed with petroleum, and South Polar skuas (*Catharacta maccormicki*) exposed to petroleum, abandoned their nest sites (Fry et al. 1986, Eppley and Rubega 1990). Pathological conditions in the blood, liver, kidneys, and glands develop when oil is consumed (summarized in Fry and Lowenstine 1985). Oil fed to herring gull chicks (*Larus argentatus*) impeded nutrient absorption, increased metabolic activity, and caused a greater food requirement (Miller et al. 1978). Lastly, cleanup activities associated with an oil spill contribute a significant disturbance to oystercatchers and other organisms living in shoreline habitats.

To assess the injury incurred by black oystercatchers as a result of the *Exxon Valdez* oil spill, the reproductive success of black oystercatchers breeding in Prince William Sound was measured in 1989 and changes in the breeding population and reproductive success in years following the spill were monitored.

Mortality of mussels in oystercatcher feeding sites was estimated and mussel samples were collected to assess petroleum hydrocarbon contamination. Behavior of oystercatchers was measured to determine if changes in prey resources and presence of oil on shorelines altered foraging behavior.

Interim reports on black oystercatcher research conducted in Prince William Sound were prepared by Sharp (1990) and Andres (1991).

OBJECTIVES

1. Monitor changes in the breeding population size during post-spill years;

2. Compare components of reproduction (clutch size, hatching success, fledging success, productivity, egg volume, and chick growth rate) between black oystercatchers nesting on oiled and unoiled beaches;

3. Determine if foraging behavior of oystercatchers was affected by oil on shorelines; and

4. Determine if oystercatcher prey populations were affected by shoreline oiling and if contaminated prey provided a possible route of exposure of oystercatchers to oil.

METHODS

Study Area

The study area was located in central Prince William Sound, Alaska, and included the Port Chalmers area of Montague Island, Green Island and Knight Island (Fig. 1). Shorelines on Green and Montague islands consisted of tidal flats, mixed sand and gravel beaches, and gravel beaches that were interspersed with rocky, wave-cut platforms. Knight Island was characterized by rocky shorelines that were interrupted by occasional patches of mixed sand and gravel or gravel beaches. Shorelines on Knight Island were steeper and had greater nearshore water depths than shorelines on Green or Montague Island. Average elevation within 300 m of the shoreline on Knight Island was 165 m, whereas average elevation on Green and Montague islands was 24 m.

Field work in Prince William Sound was conducted from 4 June 1989 to 12 July 1989 and from 30 May 1991 to 14 August 1991. In 1990, Green Island was visited from 22 to 23 June and from 2 to 3 August.

Determination of Shoreline Oiling

The first step to assess the effect of spilled oil on black oystercatchers was to determine the oiling status of shorelines in the study area. Oiling status of shorelines within the study area was determined from maps generated by the *Exxon Valdez* Oil Spill Damage Assessment Geoprocessing Group (1989, 1990) and verified by interviews of numerous researchers who visited the study area during post-spill 1989. Oiling characterizations of the intertidal zone were heavy impact (oiling band > 6 m wide or >50% coverage), moderate impact (oiling band 3-6 m wide or 10-50% coverage), light impact (oiling band <3 m or <10% coverage) or no impact (0% coverage). The amount of shoreline oiling at oystercatcher nesting and feeding sites on Green Island was independently assessed in 1989 by estimating the surficial oil covering (to the nearest 10%) at regular 1 m^2 intervals along a transect perpendicular to the waterline. Transects were selected to match areas used by oystercatcher broods. Because concern had been raised regarding the validity of oil map designations (oiling levels were thought to be too conservative, [B. E. Sharp, pers. commun.]), differences between oiling status on the oil maps and oiling status assigned by Sharp (1990) were tested.

Oiling designations of Green Island shorelines assigned by the Geoprocessing Group were higher (more moderately or heavily impacted shoreline segments) than designations assigned by Sharp (paired t-test, $t = 2.78$, $P \leq 0.025$, df = 15). Therefore, oiling categorization of shoreline segments assigned by the Geoprocessing Group was used to determine oiling status of oystercatcher nesting and feeding sites. Because mutually exclusive cleaning treatments of specific shoreline segments could not be accurately determined from cleanup records, composite oiling and cleanup disturbances to shorelines were broadly categorized as oil-affected or oil-unaffected (Highsmith et al. 1990). Comparisons of reproductive success, foraging behavior, and prey populations in 1989 were made between oiled (lightly to heavily oiled) nest sites and unoiled (no oil impact) nest sites. Analysis of data collected in 1991 focused on heavily oiled and unoiled nest sites.

Oystercatcher Populations and Reproductive Success

Two-person crews initially searched shorelines by boat or on foot to determine the presence of breeding oystercatchers. All nest sites occupied on Green and Montague islands in 1989 were checked in 1991. For each oystercatcher observation, location and status (single, pair, pair with nest) were noted. The number of breeding pairs and proportion of breeders in the population on Green and Montague islands were determined. If no evidence of nesting was found after repeated visits, the pair was considered as non-breeding. Pairs that had nests fail prior to the start of the study were also designated as non-breeders. Counts of breeding pairs and measures of reproductive success were also made, following the same procedures in the same areas, in 1992.

For nesting pairs, the number of eggs or chicks, maximum lengths and widths of eggs (1989 only), and the number of adults present were recorded. Nests were approached cautiously to avoid attracting avian predators, and most nests were approached from the water to avoid attracting mammalian predators. Nest sites were revisited every 3 to 10 days to monitor their outcome.

Components of reproductive success were estimated to determine if the *Exxon Valdez* oil spill affected the reproduction of black oystercatchers. Hatching success was calculated as the proportion of nests that hatched ≥1 chick. Fledging success was calculated as the proportion of nests that hatched ≥1 chick and that fledged ≥1 chick. Mean productivity was estimated as the average number of young that fledged from all nests. Because studies were begun after many pairs had initiated nesting, and losses due to oiling might be underestimated, hatching success was calculated 2 ways -- 1) by dividing the number of successful nests by the total number of pairs present in the study area, and 2) by dividing the number of successful nests by the number of pairs that had eggs or chicks during the study period. Adjusted hatching success estimates for the 1989 data were compared to estimates obtained during 1992 (the field season began when females were initiating clutches in mid-May). Mean clutch size and mean brood reduction were also estimated. Brood reduction was defined as the loss of chicks from hatch to either the fledgling stage (1991) or the end of the study (1989). The number of days each nest was exposed to predation in 1989 was also determined. The ultimate outcome of each pair's nesting effort, which resulted from either the first or second nesting attempt, was used for all analyses of reproductive success.

Exposure of female oystercatchers to oil through ingestion was indirectly determined by measuring volumes of eggs. Maximum length (L) and breadth (B) of eggs were measured in 1989. Nol et al.'s (1984) formula ($V = 0.51LB^2$) was used to covert egg measurements to egg volumes. The relative difference between the largest and smallest egg ($[egg_1 - egg_3]/egg_1$) was calculated for 3-egg clutches laid by females at moderately or heavily oiled sites on Green Island and at unoiled sites on Montague Island. Mean relative differences (%), and their associated variances, were calculated for oiled and unoiled groups.

Effects of oil ingestion were also assessed by measuring the growth rates of chicks. In 1991, chicks were banded with a U.S. Fish and Wildlife Service aluminum band and an unique combination of color bands when chicks were ≥7 days of age. Weights (g), bill lengths (mm), time of day (later converted to position in the tidal cycle), and age were recorded. Chick ages were determined from plumage characteristics reported by Webster (1942). After approximately 10 days, chicks were remeasured. Instantaneous change (r) in bill length and body weight were calculated according to the following equation (Ricklefs 1983):

$$r = \frac{\ln(m_2) - \ln(m_1)}{t_2 - t_1} \tag{1}$$

where,

m_x = bill length or body weight at time x, and
t_x = date of measurement

To account for differences in growth rates that resulted from genetic differences of broods or from sibling rivalry within broods (Groves 1984), the ratio of instantaneous change in weight relative to instantaneous change in bill length was calculated. This metric (r_w/r_b) should quantify the surplus energy available for weight gain in oystercatcher chicks. Use of energy for the growth of structures that are critical for the survival of the individual (e.g., the bill) reduces energy available for weight gain (O'Connor 1984). This type of growth index is commonly used in contaminant studies to determine toxin-related growth impairments (Hoffman et al. 1993). If measurements were obtained from ≥2 chicks at a nest site, indices were averaged to produce a mean growth change for each nest site.

Foraging Behavior

Feeding rates of adults and rates of food delivery to young were measured to determine the effects of the *Exxon Valdez* oil spill on the foraging behavior of oystercatchers. Feeding rates of adults (ingestions/min) during tidal minima were opportunistically collected in 1989; information was not collected on the sizes or types of prey taken.

Observations of adults feeding young were made in 1991. Each observation period began approximately 1 hour before low tide and ended 1 hour after low tide. Timed observations commenced with the first delivery of a prey item by the adult. For each subsequent delivery, the time, type of prey item, and length of the prey item (scaled to tenths of the bill) was recorded. Observers practiced identifying shelled and de-shelled (by color and shape) prey items and estimating prey lengths prior to data collection.

To standardize food consumption across varying sizes and types of prey, regressions of weight and length were constructed. Varying numbers of common prey (limpets, mussels, clams, and chitons) were segregated into 5 or 10 mm size classes and the mean weight (g) and length (mm) for each size class was calculated. Mean wet weights were regressed against mean tissue length using natural log models (Table 1). For limpets, separate regressions for *Lottia pelta*, *Techtura persona* and *T. scutum* were calculated. An overall estimate of "average" limpet wet weight for each size class was produced by weighting the estimates for each group by their representation in that size class (determined from shell collections and data from Coastal Habitat Study 1 [A. J. Hooten, Univ. Alas., unpubl. data]). Mean chiton weights were calculated in the same way.

Food consumption was standardized for varying time periods and chick weights by dividing the total prey biomass by the total biomass of each brood during the period of observation ([prey biomass/time]/chick biomass).

Prey Populations

To document the effect of the spill on prey populations of oystercatchers, the proportions of living and dead mussels were measured on 1 m^2 quadrats on Green and Montague islands during 1989. Unequal numbers of quadrats were sequentially surveyed on 2 to 4 transects selectively placed in known oystercatcher feeding sites.

Mussels were collected from oystercatcher feeding sites in 1989 for petroleum hydrocarbon analysis. Mussel samples were removed from the shell, placed in sterile jars, and immediately refrigerated. Tissue samples were sent to the Geochemical and Environmental Research Group of the Texas A&M University for gas chromatography-mass spectroscopy determination of aliphatic hydrocarbon (AH) and polycyclic aromatic hydrocarbons (PAH) concentrations. Extraction of tissue samples followed the NOAA Status and Trends Method (Macleod et al. 1985) with minor revisions (Brooks et al. 1989; Wade et al. 1988). Briefly, tissue samples were homogenized with a Teckmar Tissumizer and a 1 to 10-gram sample (wet weight) was extracted with the tissumizer by adding surrogate standards, Na_2SO_4 and methylene chloride, in a centrifuge tube. The tissue extracts were purified by silicia/alumina column chromatography to isolate the AH and PAH fractions. The PAH fraction was further purified by HPLC to remove interfering lipids. The quantitative analyses were performed by capillary gas chromatography (CGC) with a flame ionization detector for aliphatic hydrocarbons and a mass spectrometer detector in the SIM mode for aromatic hydrocarbons (Wade et al. 1988).

Dry weight was determined by weighing approximately 1 gram of wet sample and placing it into a clean, labeled, preweighed 10 ml beaker. The beaker was placed in a forced air oven at approximately 75° C for 24 hours. The beaker with the dry sample was then weighed and the % dry weight was calculated by the formula:

$$\frac{(wt.\ dry\ sample + beaker) - (wt.\ beaker)\ (100)}{(wt.\ wet\ sample + beaker) - (wt.\ beaker)} \qquad (2)$$

Details of analytical methods are in GERG standard operating procedures, SOP-8901 to SOP-8905.

Indices were calculated for determining whether petrogenic hydrocarbons were present in mussel tissues (Manen 1990) and included the pristane to phytane ratio and the Carbon Preference Index (Table 2). Concentrations of the unresolved complex mixture and total aromatic compounds were examined (Table 2).

Statistical Analysis

The primary sampling (or experimental) unit for all tests of the effect of oil on black oystercatchers was a nest site or breeding pair, except for feeding rates where an individual oystercatcher was the primary sampling unit. Standard t-tests were used to compare means of oiled and unoiled groups. Alternative hypotheses were generally constructed to indicate that oiling caused a negative effect. Satterthwaite's approximation for testing 2 population means was used to determine degrees of freedom for all t-tests (Snedecor and Cochran 1980). When sample sizes were small ($n \leq 10$ for combined groups), a two-sample randomization test (Manly 1991, including Manly's RT program) was used to test for differences between groups. P-values of test statistics were examined to determine the magnitude of the difference between oiled and unoiled groups. Multiple tests of the common null hypothesis of no oiling effect within this study, and among all the oil spill studies testing this hypothesis, precluded setting a realistic apriori α-level for test statistics. Concordance among test results was used to qualitatively assess an overall oiling effect.

Extraneous independent factors (age, brood size, tidal height), along with oiling category, were incorporated into a covariate, linear regression model of chick growth (with r_w/r_b as the dependent variable). Linear model-checking procedures involved visual inspection of residuals plotted against predicted values, correlation of residuals and predicted values, and calculation of Cook's D and tolerances. Most parametric analyses were carried out using the statistical package SYSTAT®.

RESULTS

Oystercatcher Populations and Reproductive Success

The total number of pairs on Green Island increased from 28 pairs in 1989 to 38 pairs in 1991 (36%). During the same period, the number of pairs with active nests on Green Island increased from 17 breeding pairs to 36 breeding pairs (112%). The number of breeding pairs on Montague Island, in areas that were surveyed in 1989 and 1991, remained constant at 18 pairs.

On Green Island, non-breeding pairs constituted a higher proportion of the population in 1989 (39%) than in 1991 (5%, one-tailed t-test, $t = 3.44$, $P \leq 0.005$, df = 36). Non-breeding pairs also constituted a higher proportion on Green Island than on Montague Island (9%) in 1989 (one-tailed t-test, $t = 2.72$, $P \leq 0.005$, df = 46).

The 37 nest sites located in 1989 and the 90 nest sites located in 1991 were affected differentially by shoreline oiling (Table 3). Clutch size did not differ

(P >>0.1) between oiled and unoiled nest sites in 1989 or between heavily oiled and unoiled nest sites in 1991 (Table 4). However, the relative difference between the volume of eggs laid by females at heavily or moderately oiled nest sites (14.5%) was greater than the relative difference between eggs laid by females at unoiled nest sites (8.6%, one-tailed t-test, t = 1.89, $P \leq 0.045$, df = 11). When the spill year was compared to a post-spill year when the start of fieldwork coincided with the laying of clutches, adjusted hatching success of all pairs occurring on Green Island in 1989 was depressed (35% in 1989, 75% in 1992, one-tailed t-test, t = 3.49, $P \leq 0.001$, df = 51). Adjusted hatching success of pairs nesting on unoiled Montague Island was equivalent in both years (43%). Brood loss tended to be greater for pairs nesting at heavily or moderately oiled nest sites than for pairs nesting at unoiled sites in 1989 (randomization test, D_0 = 0.3, P = 0.079, N = 252). Although studies in 1989 were concluded before chicks fledged, the mean number of days chicks were exposed to predation (14) was equivalent for pairs nesting at oiled and unoiled sites. Brood loss, measured to fledging, did not differ between pairs nesting at heavily oiled and unoiled sites in 1991 (3% difference, P >> 0.1, df = 22). On Green Island in 1990, intense cleanup activity led to differences in survival of chicks raised at disturbed and undisturbed nest sites (Fig. 3, t = 4.24, $P \leq 0.005$, df = 9,). Fledging success of chicks did not differ between pairs nesting at unoiled and heavily oiled nest sites in 1991 (10% difference, P >> 0.1, df = 21).

Although hatching and fledging success did not differ between pairs nesting at oiled and unoiled nest sites in 1991, instantaneous weight gain, relative to bill growth, of chicks raised at oiled sites was slower than growth of chicks raised at unoiled sites (R^2 = 0.34, t_{oil} = 2.23, P = 0.034). The multiple regression log model also included a significant (P = 0.005) age covariate (Fig. 3). Neither brood size nor tide height during measurements explained additional variation in growth rates.

Foraging Behavior

The mean feeding rate of adults was lower on oiled Green Island (1.40 ingestions/min) than the feeding rate of adults on unoiled Montague Island (4.24 ingestions/min) in 1989 (two-tailed t-test, t = 6.09, $P \leq 0.001$, df = 29). In 1991, delivery rates to chicks (items/hour/chick) were comparable between adults nesting at oiled and unoiled shorelines, but adults at oiled nest sites fed a higher biomass of prey (prey weight [g]/min/$\sum$ chick weight[g]) to their chicks than adults at unoiled nest sites (two-tailed t-test, t = 3.13, $P \leq 0.025$, df = 8). Although caloric values likely differed among prey types, caloric differences between grazing and filter-feeding prey varied <5% (Cummins and Wuycheck 1971), whereas prey biomass varied by several orders of magnitude.

Prey Populations

The percentage of dead mussels found in quadrats on Green Island (4.0%) was greater than in quadrats on Montague Island (1.6%) in 1989 (one-tailed $t = 3.00$, $P \leq 0.005$, df = 18). All oil contamination measures of tissue samples from Green Island mussels had higher ($P \leq 0.02$) petroleum hydrocarbon values or concentrations than samples collected on Montague Island (Table 5). Crude oil from the *Exxon Valdez* did appear to be the source of hydrocarbon contamination in mussel tissue (Fig. 4, mussel concentrations were averaged for all samples collected from oiled sites).

DISCUSSION

Estimates of direct mortality of black oystercatchers attributable to the *Exxon Valdez* oil spill vary markedly among the techniques used to assess losses. Nine oystercatcher carcasses were retrieved from the entire spill area during beach surveys for injured wildlife in 1989. Morgue counts and field experiments were used by Ecological Consulting, Inc. (1991) to derive a model of direct seabird mortality caused by the *Exxon Valdez* oil spill. Assuming that an oystercatcher carcass on a beach had a 59% chance of being found and a 31% chance of not being scavenged, the 9 collected carcasses represented about 18% of the oystercatchers that were directly killed by the spill (carcass retrieval might have been higher in the Sound, so this represents a liberal estimate of the mortality). Unlike many pelagic seabirds, oystercatcher carcasses were probably not subject to losses at sea. Thus, the model-based approach estimated that approximately 50 black oystercatchers, 3.6% of the population (of ≈ 1388 individuals) inhabiting the entire spill zone (B.A. Andres, unpubl. data), were directly killed by oil.

Population losses estimated from boat-based, waterbird surveys in Prince William Sound were much greater (Klosiewski and Laing 1994). Along shorelines in the oiled zone, estimated losses between July 1984 and July 1989 were 88 birds (22% of the population, $P = 0.063$) and between July 1984 and July 1990 were 225 birds (57%, $P = 0.003$). Between July 1984 and July 1991 a loss of 39 birds (10%, $P = 0.163$) was detected. Relative to changes that occurred in the unoiled zone of Prince William Sound between 1972-1973 and 1989-1991, the number of oystercatchers declined in the oiled zone in March ($P < 0.01$) and August ($P = 0.05$) but not in July ($P = 0.43$).

Because of the shoreline habits of oystercatchers and because few birds were occupying territories at the time of the spill, direct lethal effects of the spill on adult oystercatchers were, most likely, minimal. In fact, no oiled adults were observed on Green Island during the summer of 1989. High losses of birds estimated from boat surveys might have resulted from differences in the behavior of breeding and non-breeding birds. Unlike territorial breeders, non-breeding oystercatchers form flocks that gradually expand throughout the season and persist throughout winter. However, ≤25% of the breeding population remains in Prince William Sound in the winter (Andres 1994). Of the 3 known concentration areas of oystercatcher flocks in Prince William Sound, 2 occur in unoiled areas and the other is not bisected by any of the random transects of the USFWS boat survey. Failed breeders that dispersed from oiled areas and joined these flocks probably resulted in a large "loss" from the breeding population. Displacement of breeding adults, however, could lead to a substantial loss of reproductive potential of the population during 1989 and 1990.

The rapid change in the number of pairs occupying Green Island (36%), from 28 pairs in 1989 to 38 pairs in 1992, is indicative of a population where immigration is occurring. Although increases in breeding pairs might be caused by young birds recruiting into the breeding population at an earlier age, large numbers of individuals >2 years of age have not been observed in the Sound in early summer. Additionally, changes in the number of breeding pairs greatly exceeded the intrinsic rate of growth in other oystercatcher populations; annual increases in perturbed populations of Eurasian oystercatchers (*Haematopus ostralegus*) averaged 6.25% (Nur and Ainley 1992). Assuming a maximum loss of 57% of the population from the spill zone of Prince William Sound, the oystercatcher population would take 15 years to reach pre-spill levels (Fig. 5). Post-spill changes in the number of breeding pairs on Green Island and in the estimate of the population in the oiled zone exceeded projected recovery rates based on this maximum estimate of loss (Fig. 4). By 1991, oystercatcher pairs displaced by oil spill disturbances were reoccupying Green Island. Oiled areas on Knight Island, however, lost 5% of the breeding population between 1991 and 1992. Because birds were not marked prior to 1991, precise determination of colonizers (displaced pairs, immigrants or recruits) was impossible. The disturbance of highly territorial pairs, many that could occupy the same territory year after year (Purdy 1986), might have allowed for territory establishment by previously non-breeding pairs.

Disruption of the breeding of black oystercatchers by the spill was supported by the high proportion of pairs on Green Island (39%) that did not have nests in early June of 1989. If this displaced breeder component is subtracted from the maximum loss estimated from boat surveys, direct mortality of oystercatchers is reduced to 18% of the population inhabiting the spill area of Prince William Sound. With an 18% reduction caused by the spill, the population could recover in 5 years.

For oystercatcher pairs that tolerated oiled nest sites in 1989 and were able to hatch eggs, those that nested at heavily or moderately oiled sites experienced greater losses of chicks than pairs that nested at unoiled shorelines. That chick mortality was attributable to the spill were strengthened by the fact that the unoiled control site, Montague Island, supported a greater number of predators and had greater nest and brood predation rates (B. A. Andres, B. E. Sharp, pers. obs.). The direct observations of oiled chicks in 1989 indicated that chicks were directly exposed to oil on nesting or foraging beaches. Although studies were terminated before chicks reached the fledgling stage in 1989, reduced hatching success probably resulted in lower productivity in oiled areas. Other shoreline species had their breeding disrupted in 1989; loss of reproductive potential was documented for bald eagles (*Haliaeetes leucocephalus*) nesting in Prince William Sound (Bowman et al. MS).

Although the *Exxon Valdez* oil spill and associated cleanup activities contributed to chick mortality in 1989 and 1990, the magnitude of the effect of shoreline oiling is difficult to assess on a population level. Differences in habitat selection and corresponding breeding density and the strong effects of predation on productivity of black oystercatchers confound a determination of the loss of reproductive potential (chicks) attributable to the *Exxon Valdez* oil spill. The longevity of oystercatchers (perhaps 20 years based on their size) minimizes the importance of a single season breeding failure, but recurring reproductive failures could negatively affect the breeding population. Because of the lag time of reproductive maturation in the black oystercatcher, negative effects of the spill on recruitment, and population growth, could still occur; birds hatched in 1989 will enter the breeding population for the first time in 1994.

Besides disruption of breeding, Prince William Sound oystercatchers exhibited immediate and chronic symptoms of oil ingestion. Paramount among possible oil-ingestion effects was a lower weight gain, relative to bill growth, by chicks raised at heavily or moderately oiled nest sites. The association of increased food demand and a reduced growth rate is suggestive of petroleum hydrocarbon ingestion (Miller et al. 1978). Although fledgling survival is often correlated with fat accumulation and fledgling weight (Ricklefs 1983), fledging success did not differ between pairs nesting on oiled and unoiled sites. Parental feeding extending beyond the morphological fledging of chicks appeared to compensate for the metabolic deficiencies of chicks (Andres MS). Adults were observed provisioning chicks as old as 75 days in oiled areas of the Sound (35 - 40 days beyond fledging). Slower gains of self-sufficiency by chicks could translate into decreased juvenile survival rates.

Lower relative volume of eggs laid on oiled nest sites suggested that females were either exposed to petrogenic hydrocarbons or oil impaired their food consumption rates. Ingestion of contaminated prey, particularly blue mussels, could have provided a route of hydrocarbon exposure for black oystercatchers breeding in the oiled zone. Consistent differences between mussel samples collected from oiled and unoiled sites indicated that *Exxon Valdez* crude oil did alter the foraging habitat of black oystercatchers. Increased mortality and high hydrocarbon concentrations of mussels collected in the feeding sites of oystercatchers established the potential for exposure to oil via prey consumption. Aromatic hydrocarbon concentrations were much higher than those reported from unpolluted sites (Rainio et al. 1986). Also, many individual samples had aliphatic hydrocarbon concentrations that greatly exceeded ambient concentrations in mussels collected from Kachemak Bay, Alaska, (Shaw and Wiggs 1980) and those collected from Port Valdez, Alaska, that were subjected to chronic petroleum discharge (Shaw et al. 1986).

CONCLUSIONS

The most reasonable estimates of direct mortality of black oystercatchers attributable to the *Exxon Valdez* oil spill ranged from 50 to 280 individuals (4 - 20% of the population inhabiting the entire spill area). In the area studied, many breeding oystercatchers (≥39%) were displaced by the spill and related disturbances and few chicks were produced during 1989 and 1990. The full effect of the *Exxon Valdez* oil spill on black oystercatchers will not be known until birds hatched in years of disturbance have the potential to enter the breeding population. Oystercatchers have reoccupied many oiled breeding habitats in Prince William Sound.

Evidence from 1991 suggests that oil lingering in porous substrates might provide a source of chronic exposure for black oystercatchers. The most likely route of exposure to oystercatchers, manifested in slow growth rates in chicks, is oiled prey. High concentrations of petroleum hydrocarbons persist in mussel beds that occur on these substrates in Prince William Sound (P. Rounds, NOAA, pers. commun.). Ongoing work will directly determine if black oystercatchers are exposed to oil through the ingestion of contaminated prey and will examine the geographic magnitude of exposure of black oystercatchers to persistent oil.

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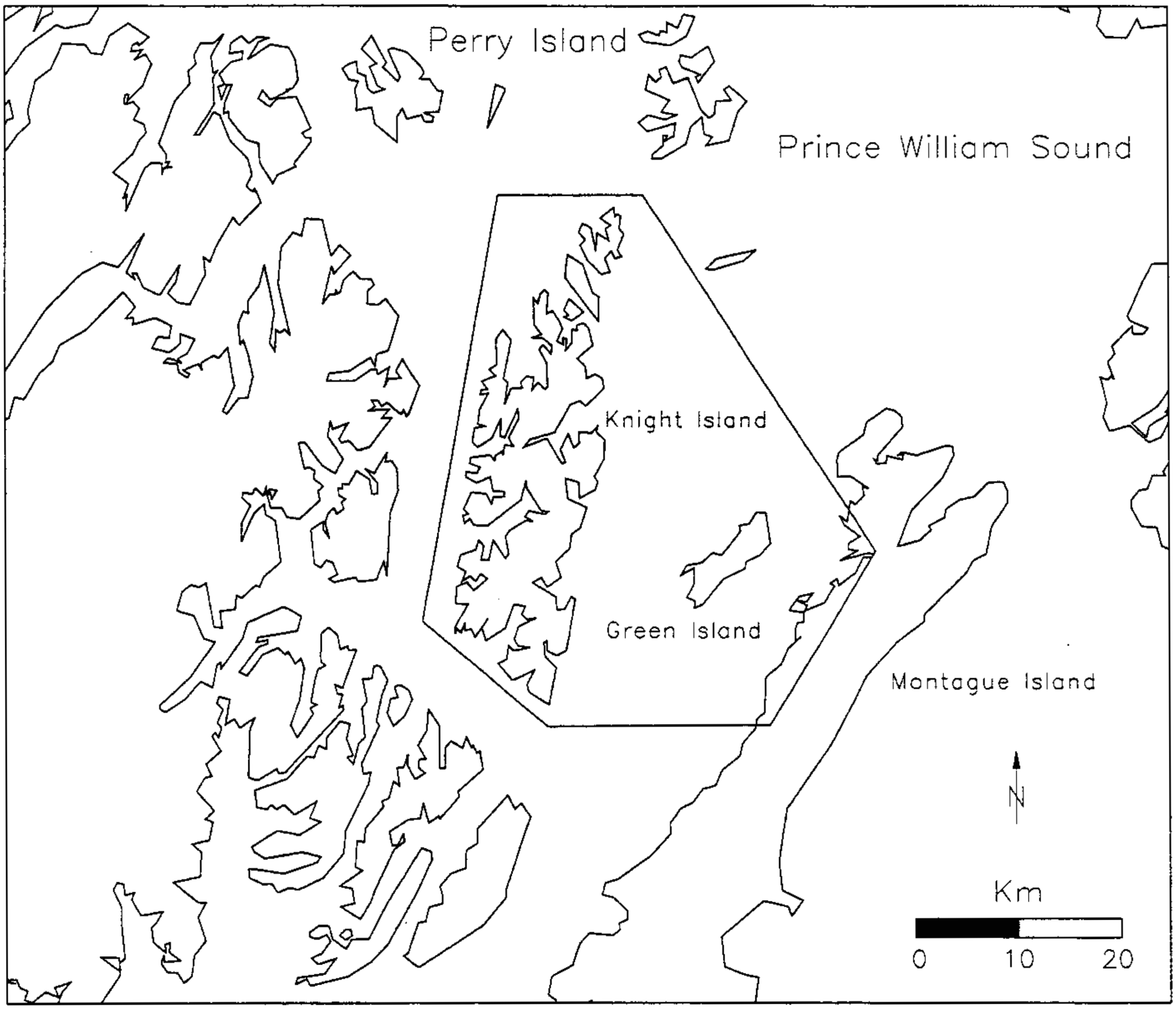

Figure 1. Location of black oystercatcher studies (1989 - 1991) on Knight, Green, and Montague islands in central Prince William Sound, Alaska.

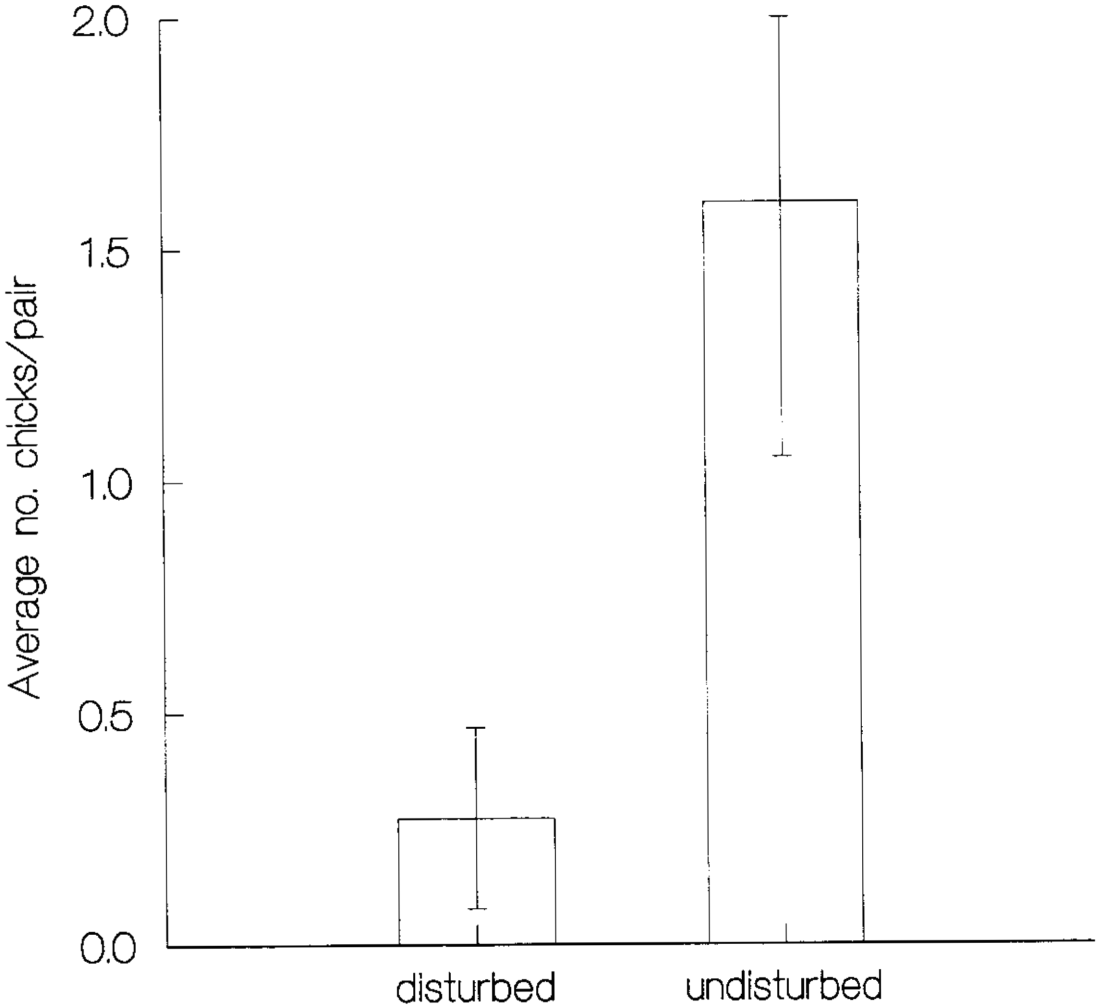

Figure 2. Average number of chicks alive after 43 days (± 1 SE) at nest sites on cleanup-disturbed shorelines (n = 11) and undisturbed shorelines (n = 5) of Green Island, Prince William Sound, Alaska - 1990.

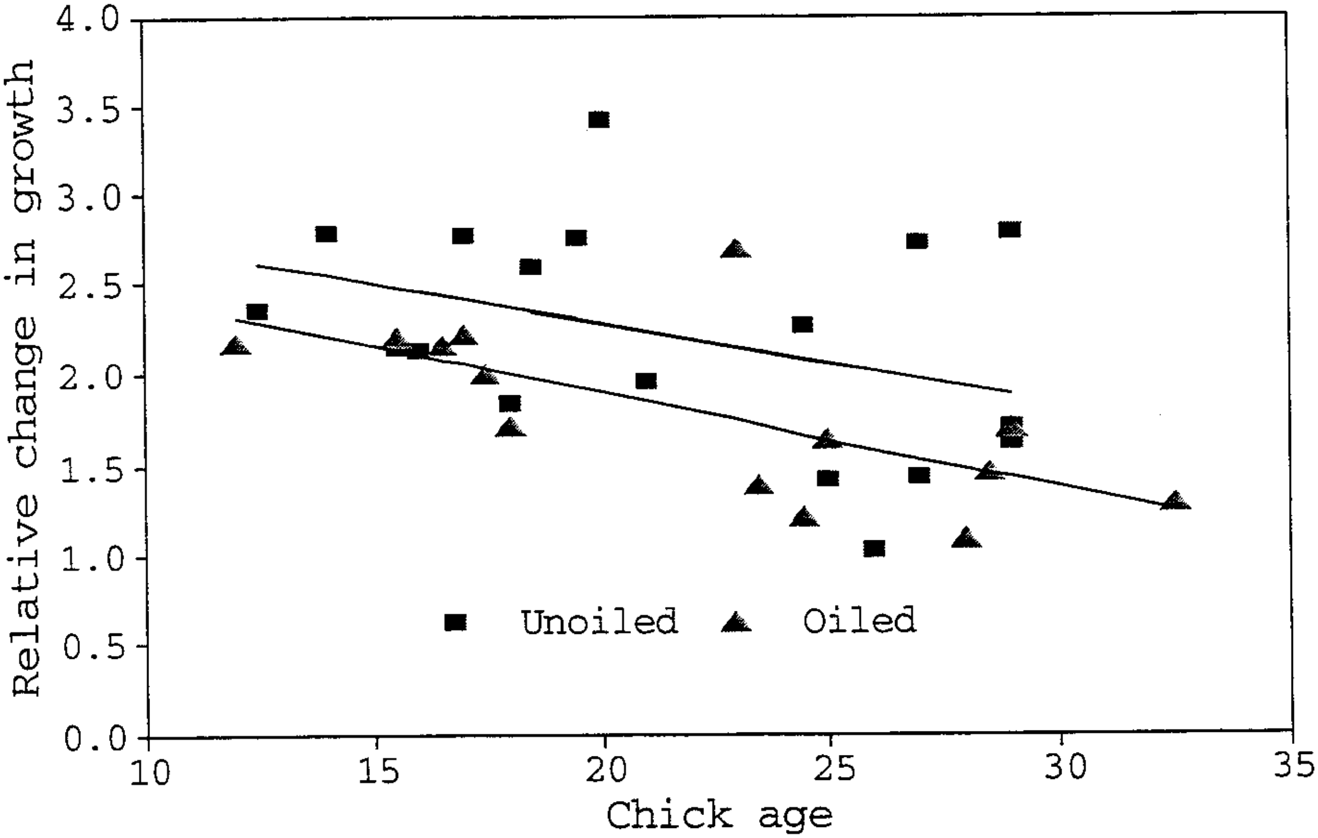

Figure 3. Age-dependent instantaneous growth index (r_w/r_b) of chicks on heavily or moderately oiled shorelines and unoiled or lightly oiled shorelines in Prince William Sound, Alaska in 1991.

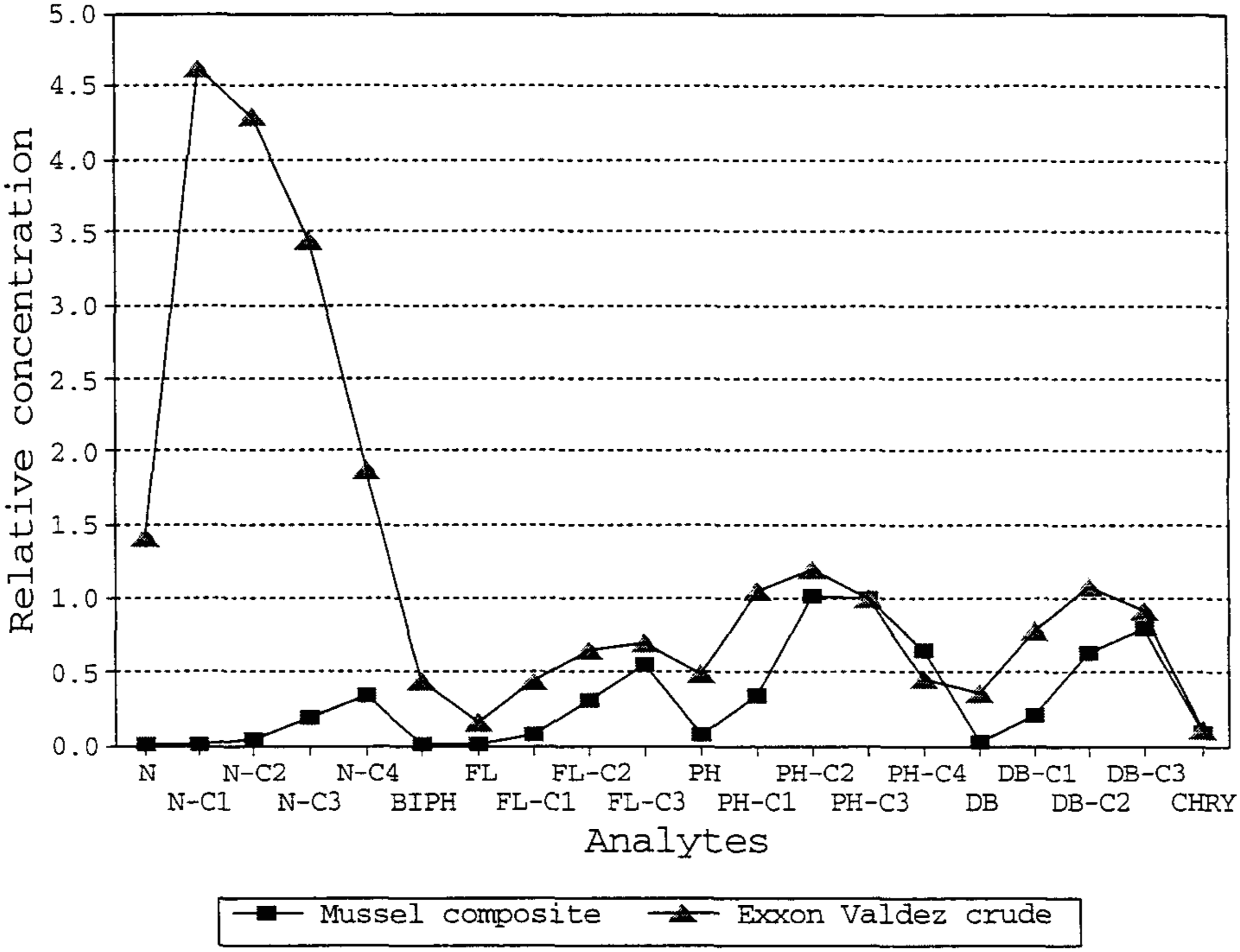

Figure 4. Relative concentrations (ng·g^{-1} dry weight, standardized by C3-phenanthrene) of polycyclic aromatic hydrocarbons in *Exxon Valdez* crude oil and mussel tissue samples from Green Island, Alaska, 1989 (N = naphthalene, BIPH = biphenyl, FL = fluorene, PH = phenanthrene, BD = dibenzothiophene, CHRY = chrysene).

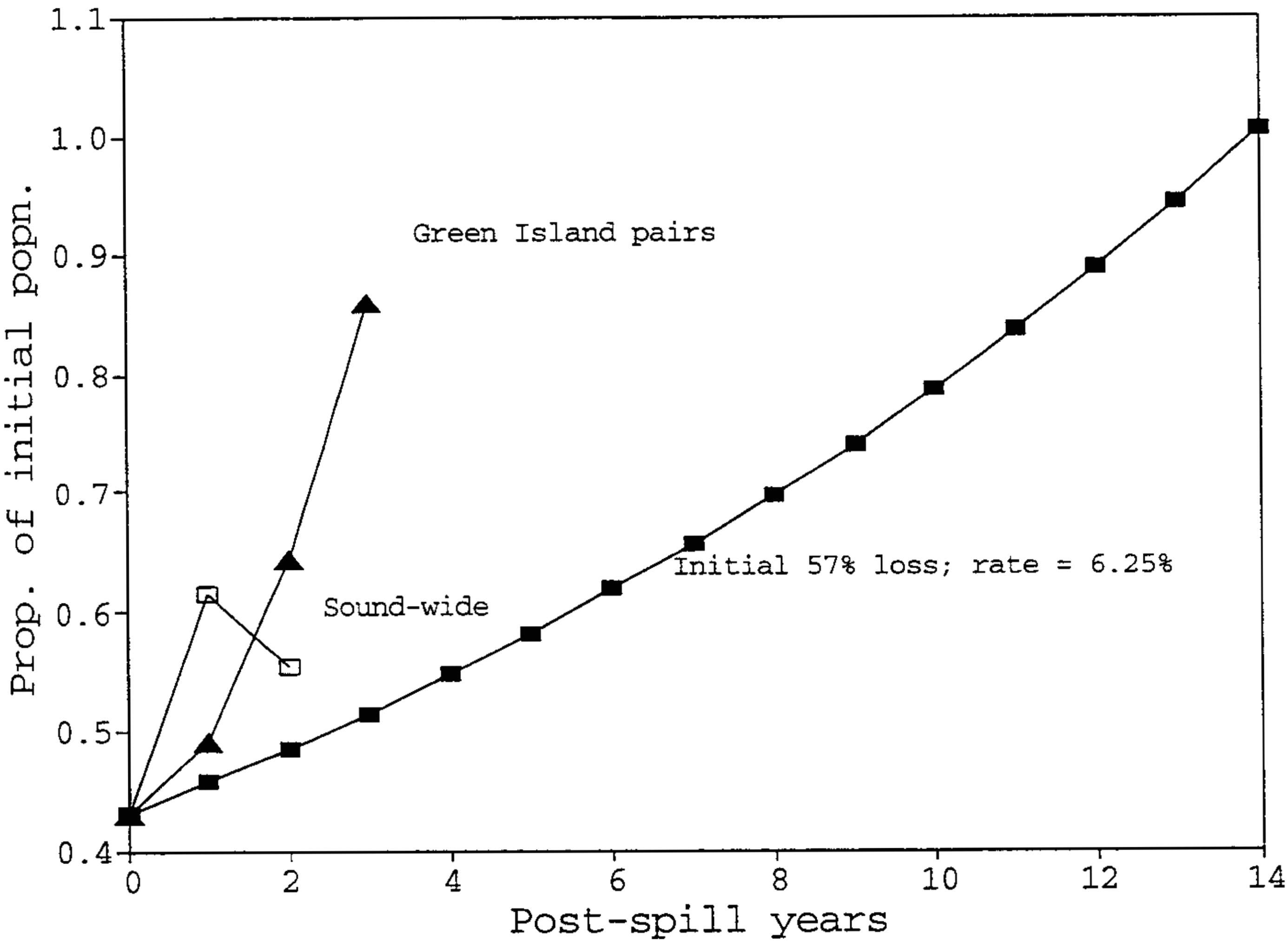

Figure 5. Theoretical recovery (r = 6.25%) of black oystercatcher populations in Prince William Sound, Alaska (assuming a 57% loss of breeding birds) and changes in actual numbers of breeding pairs on Green Island and total numbers in the oiled zone of the Sound.

Table 1. Length-weight regressions for dominant prey items of black oystercatchers in Prince William Sound, Alaska - 1991.

	Regression equation	R^2
limpets		
Lottia pelta	ln(wt) = -8.439 + 3.004 ln(lg)	0.985
Techtura persona	ln(wt) = -7.902 + 2.840 ln(lg)	0.991
T. scutum	ln(wt) = -9.276 + 3.268 ln(lg)	0.987
mussels		
Mytilus	ln(wt) = -10.003 + 2.953 ln(lg)	0.995
Modiolus	ln(wt) = -9.354 + 2.636 ln(lg)	0.997
clams (*Saxidomus, Protothaca*)	ln(wt) = -10.357 + 3.368 ln(lg)	0.998
chitons		
Katharina	ln(wt) = -6.775 + 2.246 ln(lg)	0.985
Mopalia	ln(wt) = -3.789 + 0.118 ln(lg)	0.961

Table 2. Description of indices used in analyzing petroleum hydrocarbons ($ng \cdot g^{-1}$ dry weight, $\mu g \cdot g^{-1}$ for UCM) in tissue samples and the predicted differences in oiled and unoiled matrices (from Manen 1990).

Hydrocarbon index	Index calculation	Expected direction
pristane:phytane ratio	$\frac{\text{pristane}}{\text{phytane}}$	oil<non
carbon preference index	$\frac{2(C27 + C29)}{C26 + 2(C28) + C30}$	oil<non
unresolved complex mixture		oil>non
Total aromatics	cumulative sum of all PAHs	oil>non

Table 3. Number, shoreline oiling status and location of black oystercatcher nest sites in central Prince William Sound in 1989 and 1991.

	Degree of oil impact[a]			
Year - location	None	Light	Moderate	Heavy
1989				
Green Island		2	7	5
Channel Island		3		
Montague Island	20			
1991				
Green Island		3	10	8
Little Green Island		5		
Channel Island		10		
Montague Island	18			
Bay of Isles/Marsha Bay		1	1	4
Block/Disk/Ingot/Northeast Knight islands			1	3
Drier Bay	3	2		
Herring Bay			1	4
Johnson Bay	3			
Lower Herring Bay	4	1		
Western Knight Island		3	3	2

[a] Degree of oiling is defined in the text.

Table 4. Reproductive success of black oystercatchers on oiled and unoiled sites in Prince William Sound, Alaska in 1989 and 1991.

	Clutch size			% hatched[a]			% hatched[b]			% fledged[c]			% brood loss[d]		
	mean	SE	*n*	mean	SE	*n*	mean	SE	*n*	mean	SE	*n*	mean	SE	*n*
1989 - Green and Montague Islands															
oiled	2.56	0.16	16	73.0	11.4	15	34.6	9.3	26	-			30.0	12.2	5
unoiled	2.68	0.11	19	47.4	11.4	19	42.9	10.8	21	-			0.0	0.0	5
1991 - Knight, Green and Montague Islands															
heavily oiled	2.18	0.18	22	71.4	9.9	21	-			50.0	11.2	20	34.5	12.2	14
unoiled	2.10	0.23	20	50.0	8.2	28	-			40.0	9.8	25	31.7	11.5	10

[a] percentage of nests where breeding evidence was found that hatched ≥ 1 chick.
[b] percentage of all pairs that hatched ≥ 1 chick.
[c] percentage of nests that hatched ≥ 1 chick that fledged ≥ 1 chick.
[d] percentage loss of chicks alive after 14 days to those hatched.

Table 5. Petroleum hydrocarbon concentrations ($ng \cdot g^{-1}$ dry weight, $\mu g \cdot g^{-1}$ for UCM) and index values and significance of t-test statistics for blue mussel (*Mytilus trossulus*) samples collected on Green and Montague Islands, Prince William Sound, Alaska - 1989.

Hydrocarbon index	Oiled sites mean	Oiled sites SE	Unoiled sites mean	Unoiled sites SE	df	P-value
pristane:phytane	1.49	0.15	19.98	4.33	24	≤0.001
carbon preference	1.05	0.05	2.39	0.23	26	≤0.001
total aromatics	3829	1384	173	21	24	≤0.02
unresolved complex mixture	171.4	58.6	7.4	1.7	29	≤0.01