

EFFECTS OF PERSISTENT SHORELINE OIL ON BREEDING SUCCESS AND CHICK GROWTH IN BLACK OYSTERCATCHERS

BRAD A. ANDRES¹

Ohio Cooperative Fish and Wildlife Research Unit, The Ohio State University, 1735 Neil Avenue, Columbus, Ohio 43210, USA

ABSTRACT.—To determine if Black Oystercatchers (*Haematopus bachmani*) were affected by persistent shoreline oil from the *T/V Exxon Valdez* oil spill, I identified contaminated foraging sites of oystercatchers, quantified diet and foraging behavior, assessed hydrocarbon uptake, and measured breeding success and mass gain of chicks. Hydrocarbon concentrations in sediments at foraging sites indicated that some oystercatchers potentially were exposed to shoreline oil that persisted into 1992 or 1993. Direct evidence of hydrocarbon exposure was obtained from feces of chicks raised on persistently oiled shorelines. Elevated concentrations of total hydrocarbons, even-numbered aliphatics, and unresolved complex mixtures were indicative of petroleum hydrocarbon exposure. Mussels (*Mytilus trossulus*) were an important component of the diet of adults and chicks. Oystercatchers foraged for mussels on low-sloping, mixed sand-and-gravel beaches that often retained oil but spent less time foraging on contaminated substrates than on unoiled substrates. Effects of persistent shoreline oil on measures of breeding success were negligible and likely were overridden by the influence of egg and chick predation. Chicks raised on shorelines that were heavily oiled in 1989 gained mass at a slower rate than did chicks raised on shorelines that were not heavily oiled; however, slower mass gain did not translate into reduced fledging success of chicks raised on heavily oiled shorelines. Although some oystercatchers were exposed to persistent shoreline oil, areas of contamination were patchily distributed, and relatively few adults and young were exposed. The lack of a large-scale change in oystercatcher numbers inhabiting the oiled area of Prince William Sound suggests that the negative effects of oil exposure operated locally. Consequently, oiled mussel beds present little additional risk to the population of Black Oystercatchers inhabiting Prince William Sound. Received 4 February 1998, accepted 6 November 1998.

ABOUT 40% OF THE 42 MILLION LITERS OF CRUDE OIL spilled by the *T/V Exxon Valdez* on 24 March 1989 influenced 563 km of shoreline in Prince William Sound (hereafter, "Sound"), Alaska (Galt et al. 1991). Although oiling was heaviest along shorelines in the central and southwestern portion of the Sound, oil deposition was patchy, and some shorelines remained unoiled. Within two weeks after the spill, only 5% of the oil was floating in the Sound (Galt et al. 1991); the remainder (55%) exited the Sound, evaporated, or dispersed into the water column. Because oil that washed ashore persisted longer than oil that remained in the water column, bird species that inhabited shorelines and nearshore waters were subjected to prolonged exposure to oil and were

among the species most heavily influenced by the initial effects of the spill (Wiens et al. 1996).

Extensive efforts to remove persistent oil from shorelines occurred from 1989 to 1992 (Piper 1993). Shorelines containing mussel (*Mytilus trossulus*) beds, however, were intentionally left undisturbed during clean-up operations (Babcock et al. 1994). The decision to avoid clean-up at mussel beds was based on the importance of mussels as a food source for intertidal consumers and as a structuring element of the intertidal community. Subsequently, samples collected from sediments beneath some mussel beds in the Sound indicated persistence of petroleum hydrocarbons that exceeded concentrations before the spill (Babcock et al. 1994, 1996). Fine sediments with high concentrations of hydrocarbons occurred on shorelines subject to low wave energy; after an oil spill, this shoreline type is prone to long-term oil retention (National Research Council 1985). The persistence of oil in these mussel beds raised questions about chronic exposure

¹ Present address: U.S. Fish and Wildlife Service, Nongame Migratory Bird Management, 1011 East Tudor Road, Anchorage, Alaska 99503, USA. E-mail: brad.andres@fws.gov

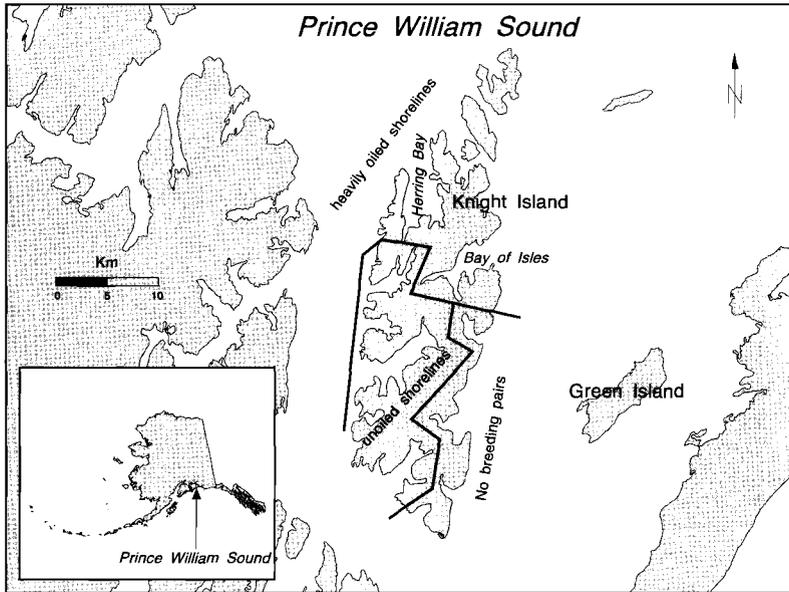


FIG. 1. Location of heavily oiled versus not heavily oiled shorelines in 1989 on Knight Island, Prince William Sound, Alaska.

of mussel consumers to petroleum hydrocarbons.

Although consumption of petroleum-contaminated food is seldom lethal, deleterious effects of oil ingestion on reproduction of marine birds include: (1) reduced parental care (Trivelpiece et al. 1984; Butler et al. 1986, 1988; Fry et al. 1986), (2) reduced clutch initiation or hatching success (Ainley et al. 1981, Fry et al. 1986, Butler et al. 1988), and (3) reduced mass gain in chicks (Miller et al. 1978; Butler and Lukasiewicz 1979; Peakall et al. 1980, 1983; Trivelpiece et al. 1984; Boersma et al. 1988). The negative effect of oil on mass gain has been the most consistent finding among studies of oil exposure (see Clark 1984) and is most pronounced during the posthatching period of the chicks. Most studies addressing the effects of oil ingestion on marine birds have involved dosing free-living or captive individuals with known quantities of oil; virtually no studies have documented the effects of long-term exposure of birds to oil that persists *in situ* on shorelines after a spill.

Territories of Black Oystercatchers (*Haematopus bachmani*) breeding in the Knight Island archipelago overlapped the area where most contaminated mussel beds were found in the Sound (Babcock et al 1996). Because of their ex-

tensive use of intertidal areas for foraging on mussels (Webster 1941, Andres and Falxa 1995), Black Oystercatchers had the potential to be exposed to shoreline oil. Therefore, I undertook a study to determine if oystercatchers were exposed to persistent shoreline oil by evaluating their foraging sites for the presence of oil, quantifying their foraging behavior and use of mussels as a food source, and assessing their intake of petroleum hydrocarbons. Having ascertained that some Black Oystercatchers were exposed to persistent shoreline oil, I hypothesized that measures of breeding success and mass gain by chicks would differ between pairs that had territories along shorelines that were heavily oiled in 1989 (the area where persistent shoreline oil was found) and those that lived along shorelines that were not heavily oiled in 1989.

METHODS

Study area and location of nests.—The Knight Island archipelago lies in central Prince William Sound, Alaska (ca. 60°30'N, 147°00'W; Fig. 1). The islands in the archipelago are characterized by convoluted shorelines, deep bays (water depth to 238 m), and uplands consisting of bogs and conifer forests. In general, the shorelines are steep and rocky, but throughout the archipelago they are interspersed

with mixed sand-and-gravel beaches; all of the shorelines are influenced by a large-amplitude diurnal tide (mean tidal range 3.8 m). Northern and eastern shorelines of the archipelago were heavily affected by the oil spill, and most of the persistently oiled mussel beds identified in the Sound in 1991 were located along these shorelines. To reduce spatial variation among oystercatcher territories, I restricted my study to the archipelago because of the similarity of shoreline habitat throughout this area (compared with other areas of the Sound). From previous work in 1991, I also found that foraging behavior was similar among pairs in the archipelago; most pairs nested on small offshore rocks and commuted to foraging areas. Although I focused on Knight Island, I made periodic visits to Green Island to collect information on breeding success. My general design followed that suggested by Wiens and Parker (1995) for analyses of the effects of environmental accidents on wildlife.

From May to August, 1992 and 1993, crews of two or three people searched 430 km of shoreline, by boat or on foot, to locate composite nesting/foraging territories of Black Oystercatchers. We located 41 pairs, 17 of which nested along shorelines that had been heavily oiled in 1989; no oystercatchers were found nesting along the southeastern shoreline of Knight Island (Fig. 1). Because persistently oiled mussel beds occurred on shorelines that were heavily oiled in 1989, I tested for broad effects of shoreline oil by comparing oystercatcher territories located on heavily oiled shorelines with those on shorelines that were not heavily oiled (un-oiled). Heavily oiled was defined as oiling that exceeded 6 m in width or covered more than 50% of a shoreline segment (100 to 600 m) of the same shoreline type (Sundberg et al. 1996). I also examined relationships among sites where persistent shoreline oil was found in 1992 or 1993. The primary sampling (or experimental) unit for all statistical tests was a territory/breeding pair.

Determination of exposure.—Foraging sites of pairs nesting along shorelines that were heavily oiled in 1989 were searched for visible and olfactory indications of oil. If oil was detected, three sediment samples, each consisting of 6 to 10 subsamples, were collected, 0 to 2 cm below the mussels along a 15- to 50-m transect through the densest part of the mussel bed. Samples were kept frozen in the field and transferred to the National Oceanic and Atmospheric Administration's Auke Bay Laboratory at the end of August. Sediment samples were screened by ultraviolet fluorescence, which provides an accurate assessment of the presence of hydrocarbons (see Babcock et al. 1994, 1996).

To further determine whether Black Oystercatchers were exposed to persistent shoreline oil, I quantified their diet, foraging behavior, and foraging-habitat use. Pairs were observed during an interval 2 h before low tide and 1 h after low tide, the period

when most foraging activity occurs. Each member of the pair was watched continuously and foraging and nonforaging behaviors were recorded ($n = 25$ pairs, 345 h of observation). The proportion of time spent foraging and incubating, relative to all activities, was calculated for each pair at each nest site. Prey choice by adults foraging during tidal minima was measured to determine the use of mussels for food. Consumption of shelled and shell-less food items was enumerated by observers who practiced identifying shell-less food items by flesh color and shape prior to data collection. I also estimated prey length scaled to tenths of the bill length of the foraging bird (see Cayford and Goss-Custard 1990). To convert lengths to biomass, I used natural log models to regress mean wet mass against mean tissue length for various food types (R^2 ranged from 0.961 to 0.998, see Andres 1996). Specific foraging sites were delineated and distance from the nest to the center of foraging sites was determined. Substrates of foraging sites were recorded, following Sundberg et al. (1996), as gravel (mixed sand-and-gravel beaches, gravel beaches) or rocky (sheltered rocky shores, exposed rocky shores, exposed wave-cut platforms).

Fecal samples were collected in 1993 to determine if oystercatcher chicks were exposed to oil that persisted in sediments. Chicks (at least seven days old) were placed in a clean Teflon pan for up to 10 min to collect feces. Excreta were transferred by a clean pipette to an HC-grade sterilized jar containing about 20 mL of dichloromethane. All reusable equipment underwent standard detergent-acetone-hexane washing between sample collections. Samples were frozen in the field and remained frozen during transportation and shipping. Multiple samples were collected from chicks at as many nest sites as possible to maximize the chance of detecting hydrocarbons. All within-nest samples were pooled before analyses.

Fecal samples were sent to the Geochemical and Environmental Research Group (GERG) at Texas A&M University for gas chromatography-mass spectroscopy determination of aliphatic hydrocarbon (AH) and polycyclic aromatic hydrocarbon (PAH) concentrations. Extraction of fecal samples followed the National Oceanic and Atmospheric Administration's Status and Trends Method for tissue samples (Macleod et al. 1985) with minor revisions (Wade et al. 1988). Briefly, fecal samples were homogenized with a Teckmar Tissumizer and a 1- to 10-g sample (wet mass) was extracted with the tissumizer by adding Na_2SO_4 and methylene chloride in a centrifuge tube. The fecal extracts were purified by silica/alumina column chromatography to isolate the AH and PAH fractions. The PAH fraction was further purified by high-performance liquid chromatography to remove interfering lipids. Quantitative analyses were performed by capillary gas chromatography with a flame ionization detector for aliphatic hydro-

carbons and a mass spectrometer detector in the SIM mode for aromatic hydrocarbons (Wade et al. 1988). Details of analytical methods are in GERG standard operating procedures, SOP-8901 to SOP-8905 (Alaska Resources Library and Information Service, Anchorage).

Because precise dry masses of samples were not determined in the laboratory, I used ratios of hydrocarbon (HC) concentrations to determine oil exposure. I used the following indicators to determine petroleum hydrocarbon contamination (Farrington et al. 1973, Hall and Coon 1988, Manen 1990, Paasivirta 1991:165–179): C17 (n-heptadecane)/phytane, odd/even HCs (C24–C29), unresolved complex mixture (branched aliphatics)/resolved aliphatic HCs, and PAHs (polycyclic aromatic hydrocarbons)/all resolved HCs. Because the purpose of these analyses was to compare petroleum hydrocarbon indices between persistently oiled and unoiled groups, minimum detection limits were subtracted from reported hydrocarbon concentrations before calculations.

Effects on breeding success and chick growth.—I measured components of breeding success to determine if persistent shoreline oil affected reproduction of Black Oystercatchers. When nesting pairs were located, observers recorded the number of eggs or chicks present and measured the maximum length and width of eggs. Nests were revisited every 3 to 10 days to monitor their state. From this information, I calculated (1) clutch size, (2) hatching success (no. eggs hatched/no. eggs laid), (3) fledging success (no. chicks reaching 40 days/no. eggs laid), (4) nesting success (no. of nests hatching more than one chick/total no. of nests), (5) productivity (no. of young fledged/no. of nests), and (6) renesting (proportion of females that renested after losing eggs or chicks more than seven days old). Except for clutch size and egg volume, where I determined size for first and second clutches, the ultimate outcome of each pair's nesting effort, which resulted from either the first or second nesting attempt, was used for all analyses. I also calculated egg volumes to determine indirectly if breeding females were exposed, through ingestion, to persistent oil. I used Nol et al.'s (1984) formula (volume = $0.51LB^3$) to convert egg measurements to egg volumes; only complete clutches (three eggs) were used in this analysis.

Because predation can have a significant effect on breeding success, I attempted to determine the abundance of one avian predator living in the vicinity of oystercatcher pairs. I conducted point counts (one point at the nest, and one or two points located 1 km from the nest) at each nest site. At each point, I recorded the presence or absence of Common Ravens (*Corvus corax*) during a 3-min period. To compare with data from Knight Island, I also counted ravens on nearby Green Island (see Andres 1997). Although other birds depredate oystercatcher eggs and chicks, previous observations indicated that territorial oys-

tercatchers reacted most vigorously to the presence of ravens, and I suspected that ravens were the most important predator on eggs and chicks. Mammalian predators such as mink (*Mustela vison*), river otter (*Lutra canadensis*), and sea otter (*Enhydra lutris*) also might prey on oystercatcher eggs and chicks, but I was unable to accurately quantify their abundance.

Because young birds are most sensitive to the negative effects of exposure to oil (Holmes and Cronshaw 1977), I measured body mass (g), tarsus length (mm), and bill length (mm) of chicks at intervals of 7 to 10 days. Chick ages were determined from plumage characteristics reported by Webster (1942) and were checked against chicks of known hatching date. I also recorded stage of the tidal cycle when measurements were made as an indication of a feeding or nonfeeding period.

To account for the effect of food provisioning on chick growth, I quantified the type and size of food fed to chicks during low tide. Each observation period began approximately 2 h before low tide and ended 1 h after low tide (as described above for adults). I standardized food consumption by dividing the rate of biomass delivered by the total biomass of each brood at the time of observation ([prey biomass/time]/total chick biomass).

Data analysis.—I used a ratio estimator (Snedecor and Cochran 1980:455–457) and a two-sample randomization procedure (Manly 1991:43–63) to compare estimates between heavily oiled and unoiled groups. For territories where persistent oil was found, I examined relationships among sediment hydrocarbon concentration and hydrocarbon indices of foraging behavior, chick feces, and chick mass. Alternative hypotheses generally were constructed to indicate that oiling caused a negative effect on estimated parameters. Satterthwaite's approximation for testing two population means was used to determine degrees of freedom for all *t*-tests (Snedecor and Cochran 1980); for small samples, I used the Mann-Whitney *U*-test for testing oiling effects. The number of iterations performed in randomization tests was set at 5,000 unless sample sizes were small; then the number of complete iterations was calculated as $n!/(n_1!n_2!)$. Because I tested multiple null hypotheses of no oiling effect, it was difficult to set an appropriate *a priori* α -level for statistical significance. Therefore, I used *P*-values of test statistics to evaluate the strength of the evidence for rejecting a null hypothesis of no oil effect.

Instantaneous change in body mass (*r*) was calculated after Butler and Lukasiewicz (1979) as:

$$r = [\ln \text{mass}_2 - \ln \text{mass}_1] / [\text{day}_2 - \text{day}_1]. \quad (1)$$

Because younger chicks are more susceptible to effects of oil ingestion, I regressed *r* against chick age for chicks ≤ 20 days (about one-half the age at fledging) and for those > 20 days. If measurements were obtained from more than two chicks at a nest, indices

TABLE 1. Consumption of mussels by adult Black Oystercatchers and delivery of mussels to chicks on heavily oiled versus not heavily oiled shorelines, Knight Island, Prince William Sound, 1991 to 1993. Values are $\bar{x} \pm SE$, with coefficient of variation in parentheses.

Variable	Heavily oiled in 1989	Not heavily oiled in 1989
	Adults	
No. of sites	8	10
No. mussels eaten/h	30.2 \pm 5.7 (0.19)	58.1 \pm 3.5 (0.06)
Biomass eaten/h (g)	13.1 \pm 2.5 (0.19)	21.0 \pm 5.0 (0.24)
	Chicks	
No. of sites	10	11
No. of mussels delivered/h	1.6 \pm 0.4 (0.25)	3.8 \pm 1.2 (0.31)
Biomass delivered/h (g)	0.5 \pm 0.2 (0.40)	1.3 \pm 0.5 (0.38)

were averaged to produce a mean growth change for each nest site. Because the same nest sites were used in multiple years, I also averaged across years to obtain a single estimate for each nest site. Extraneous independent factors (age, brood size, tidal height), along with oiling category, were incorporated into a covariate-interaction linear regression model of chick growth (with mass change as the dependent variable). I also used an age-covariate model to examine the effect of oil on mass of older chicks. 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. I used Kendall's test of concordance to examine the relationship between hydrocarbon concentrations in sediment samples and those in fecal samples. Regression analyses were conducted with SYSTAT, *t*-tests were calculated in a Quattro Pro macro, and randomization tests were executed using Manly's (1991) RT program.

RESULTS

Determination of exposure.—Ten foraging sites of Black Oystercatchers contained detectable signs of oil in 1992 and 1993. Hydrocarbon concentrations, measured as total oil equivalents ($\mu\text{g/g}$ wet mass) in sediments at these sites ($\bar{x} = 4,897 \pm SE$ of 1,624, $CV = 32\%$), exceeded concentrations at two unoiled control sites ($<1 \mu\text{g/g}$; Mann-Whitney $U = 20.0$, $n = 12$, $P = 0.031$). Within a foraging site, variability in hydrocarbon concentrations among samples (average $CV = 26\%$) was only slightly lower than variability among foraging sites. Sediments with the highest concentrations of hydrocarbons occurred in oystercatcher territories on northern and eastern Knight Island. Although mussel samples from oystercatcher foraging areas were not analyzed for oil, substantial hydrocarbon concentrations (>0.5 ppm total

polynuclear aromatic hydrocarbons) were found in mussels from other areas of Knight Island and provided a link between sediment contamination and mussel contamination (Babcock et al. 1996). However, hydrocarbon concentrations recorded in sediments were below levels toxic to mussels (Short and Harris 1996). Most of the persistently oiled oystercatcher foraging sites contained only moderately dense aggregations of mussels ($<1,000$ mussels/ m^2) and often were located on beaches composed of fine sediments, particularly in the spaces between shoreline rocks.

Mussels were an important component of the diet of adult oystercatchers inhabiting shorelines that had been heavily oiled in 1989. Most of the prey items (55%, $n = 1,082$) selected by foraging adults ($n = 13$ pairs) were mussels; however, mussels constituted only 27% of the biomass of invertebrate prey captured by adults. Adults breeding in areas of unoiled shorelines consumed more individual mussels ($t = 4.16$, $df = 14$, $P = 0.001$), but not more mussel biomass ($t = 1.40$, $df = 10$, $P = 0.2$), than adults on heavily oiled shorelines (Table 1). Prey density and diversity did not appear to differ among heavily oiled and unoiled foraging areas (pers. obs.).

Mussels constituted 42% of all prey items and 23% of all prey biomass that adults fed to their chicks ($n = 21$ nests). Adults foraging in unoiled areas tended to deliver the same number ($t = 1.82$, $df = 12$, $P = 0.09$) and the same biomass of mussels ($t = 0.44$, $df = 13$, $P > 0.5$) as did adults foraging in oiled areas (Table 1).

Most of the foraging commutes (62%, $n = 52$) by oystercatchers at the Knight Island archipelago ($n = 10$ pairs) that were more than 100 m from the nest site were made to mixed sand-and-gravel shorelines. This habitat, however,

TABLE 2. Indices of petroleum hydrocarbon concentrations and expected direction for an oiling effect in feces of Black Oystercatcher chicks raised in 1993 on shorelines heavily oiled versus not heavily oiled in 1989, Prince William Sound. Values are $\bar{x} \pm SE$, with n in parentheses.

Hydrocarbon index	Direction	Heavily oiled	Unooled
C17/phytane	<	7.0 \pm 1.3 (8)	12.4 \pm 2.7 (9)
Odd/even (C24–C29)	<	4.1 \pm 0.6 (8)	7.3 \pm 0.9 (12)
UCM/resolved aliphatics	>	22.7 \pm 4.8 (10)	11.1 \pm 3.1 (10)
PAH (%)	>	6.4 \pm 2.1 (9)	7.1 \pm 0.9 (12)

constituted only 25% of the shoreline in areas where oystercatchers foraged. Adult oystercatchers did not completely avoid persistently oiled beaches and were observed foraging on them. However, at two territories where detailed foraging data were collected, adults spent less time feeding on oiled substrates than they did on unooled substrates; a pair nesting in Bay of Isles spent much less time foraging on oiled substrates ($D_o = 9.1$ min, $I = 495$, $P = 0.01$) than did a pair nesting on Block Island ($D_o = 6.3$ min, $I = 5,000$, $P = 0.05$). Similarly, pairs that had persistently oiled substrates adjacent to their nest spent a greater proportion of time foraging at sites more than 100 m from their nests (Mann-Whitney $U = 9.0$, $n = 6$, $P = 0.046$).

Several indices of hydrocarbon concentrations calculated from feces of chicks that were raised on heavily oiled shorelines differed from those raised on unooled areas (Table 2). Differences in indices between oiled and unooled groups, in the direction expected for oil contamination, were evident for C17 (n-heptadecane) / phytane ($D_o = 5.4$, $I = 5,000$, $P = 0.028$), odd/even aliphatics ($D_o = 3.2$, $I = 5,000$, $P = 0.006$), and unresolved complex mixture (UCM)/resolved aliphatics ($D_o = -11.5$, $I = 5,000$, $P = 0.025$). Proportions of PAHs in feces did not differ between oiling groups ($D_o = 0.7\%$, $I = 5,000$, $P = 0.608$). Only the unre-

solved complex mixture index of chick feces was concordant with sediment hydrocarbon concentrations where the chicks were raised (Table 3). The highest proportions of PAHs and the highest values of the UCM/resolved aliphatics index in chick feces were recorded from sites where sediment hydrocarbon concentrations exceeded 6,000 ppm.

Effects on breeding success and chick growth.—No measures of breeding success differed significantly between pairs nesting on heavily oiled shorelines and those nesting on unooled shorelines (Table 4). Negligence of parental care by adults toward their eggs did not explain differences in nesting success between oiling groups. Pairs that inhabited heavily oiled shorelines did not spend a lower proportion of time incubating their eggs than did pairs that inhabited unooled shorelines ($D_o = -0.84$ min/h of observation, $I = 5,000$, $P = 0.66$).

Predation by Common Ravens appeared to have a large effect on oystercatcher productivity. Pairs nesting on Green Island (which was oiled in 1989) were more productive (0.81 ± 0.11 young/pair, $n = 49$) than pairs nesting on heavily oiled shorelines on Knight Island (1992 and 1993 combined; Table 4). In fact, productivity on Green Island in 1992 (1.15 young/pair) greatly exceeded productivity in all areas of Knight Island (0.39 young/pair) that same year. Shorelines on Green Island were cleaned extensively in 1989 and 1990, and the island had no persistently oiled beaches in 1992. As important, Common Ravens were detected at only 5% of the points on Green Island ($n = 20$) but at 22% of the points on Knight Island ($n = 78$). Breeding density of oystercatchers and shoreline characteristics important for use by oystercatchers (Andres 1998) did not differ among heavily oiled and unooled areas (Table 5).

Chicks raised on heavily shorelines gained

TABLE 3. Kendall's K statistics, associated sample sizes, and P -values for measures of concordance among sediment hydrocarbon concentrations and hydrocarbon contamination indices of feces collected from Black Oystercatcher chicks in Prince William Sound, 1993.

Hydrocarbon index	Kendall's K	n	P
C17/phytane	7	6	0.136
Odd/even (C24–C29)	5	7	0.281
UCM/resolved aliphatics	18	8	0.016
PAH (%)	10	8	0.138

TABLE 4. Measures of breeding success of Black Oystercatcher pairs nesting on heavily oiled versus not heavily oiled shorelines in Prince William Sound, 1992 and 1993. Values are $\bar{x} \pm SE$, with n in parentheses.

Variable	Heavily oiled in 1989	Not heavily oiled in 1989
Clutch size, 1st attempt	2.34 \pm 0.17 (16)	2.61 \pm 0.09 (22)
Clutch size, 2nd attempt	2.71 \pm 0.18 (7)	2.33 \pm 0.24 (13)
Hatching success (%)	49.6 \pm 9.3 (16)	31.1 \pm 6.0 (24)
Fledging success (%)	17.1 \pm 4.7 (16)	11.7 \pm 3.7 (24)
Nesting success (%)	30.9 \pm 7.4 (16)	24.2 \pm 5.3 (24)
Productivity (young/pair)	0.48 \pm 0.13 (16)	0.37 \pm 0.11 (24)
Females renested (%)	63.6 \pm 14.5 (11)	65.0 \pm 10.7 (20)
Egg volume, 1st clutch (3 eggs)	43.0 \pm 0.7 (14)	43.3 \pm 0.5 (12)
Egg volume, 2nd clutch (3 eggs)	41.9 \pm 1.6 (5)	44.2 \pm 0.9 (4)

mass more slowly than chicks raised at unoiled sites. With age as a significant covariate in a regression model, oiling had a significant negative effect on instantaneous mass change of chicks less than 20 days old ($F = 6.07$, $df = 1$ and 17 , $P = 0.025$) and of chicks more than 20 days old ($F = 5.47$, $df = 1$ and 11 , $P = 0.039$). In addition, a significant ($P = 0.02$) interaction between oil and chick age was evident for mass change in chicks that were 20 days old or less. Neither brood size nor tidal height explained additional variation in mass change. Differences in mass gain by chicks appeared to diminish as chicks grew older; oil, when controlling for chick age, did not explain differences in masses of older chicks ($F = 0.69$, $df = 1$ and 14 , $P = 0.42$). Mass change in chicks was only weakly concordant with sediment hydrocarbon concentration ($K = 7$, $n = 6$, $P = 0.136$).

Differences in food provisioning between adults living on heavily oiled shorelines and those living on unoiled shorelines did not explain differences in mass gain of chicks. Adults delivered food at the same rate on unoiled and heavily oiled shorelines ($t = 1.52$, $df = 18$, $P = 0.15$) and brought the same biomass in each delivery ($D_0 = 0.7$ g, $I = 5,000$, $P = 0.11$). Prey biomass relative to brood biomass delivered per hour to chicks on heavily oiled shorelines ($\bar{x} =$

2.2%) was highly variable among pairs ($CV = 41\%$) and did not differ from that on unoiled shorelines ($\bar{x} = 4.2\%$; $t = 1.2$, $df = 16$, $P = 0.26$). Because oystercatchers foraged on a variety of shoreline substrates, prey selection varied considerably among pairs; individual preference for certain prey items also may have contributed to variation among pairs within an oiling group.

DISCUSSION

Because nesting/foraging territories of Black Oystercatchers breeding in the Knight Island archipelago overlapped with contaminated mussel beds, some pairs were susceptible to persistent shoreline oil, particularly on northern Knight Island. All contaminated sites consisted of fine sediments or were in spaces between shoreline rocks. The reliance of oystercatchers on mussel prey, and their high use of mixed sand-and-gravel shorelines for foraging, suggested that the exposure route for oystercatchers was via a trophic pathway. Although I did not directly determine hydrocarbon concentrations in mussels from oystercatcher foraging sites, mussels living on contaminated sediments in other areas of the Sound had detectable concentrations of petroleum hydrocar-

TABLE 5. Characteristics of the environment and density of Black Oystercatchers on heavily oiled versus not heavily oiled shorelines on Knight Island, Prince William Sound, 1992 and 1993.

Environmental feature	Not heavily oiled in 1989	Heavily oiled in 1989
Mean shoreline elevation (m) within 300 m ($n = 213$)	155	133
Shoreline (%) in mixed sand-and-gravel ($n = 430$ km)	40	27
Density (per km) of islets ($n = 430$ km) ^a	1.7	2.1
Occurrence (%) of Common Ravens ($n = 78$ points)	20.5	29.2
Density (per km) of oystercatchers ($n = 41$ pairs)	0.098	0.086

^a Islets = less than 100 m in diameter.

bons (Babcock et al. 1996). Distribution of hydrocarbon components in sediment samples confirmed that *Exxon Valdez* crude oil was the source of persistent oil in Prince William Sound (Babcock et al. 1996).

Although oystercatchers foraged on persistently oiled shorelines, pairs with territories that contained both persistently oiled and un-oiled foraging sites spent less time feeding at the former; mussel densities on persistently oiled and un-oiled substrates were similar and did not appear to influence differential use of these areas. The lower use of persistently oiled substrates suggests that adult oystercatchers were able to detect contaminated sediments or prey. I occasionally observed adults rejecting prey items, but only on persistently oiled substrates. The presence of persistent shoreline oil might have dissuaded adults from consuming mussels; however, adults foraging in areas of oiled shorelines ingested as much mussel biomass as adults in un-oiled areas. The use of multiple foraging sites, and the high variability of hydrocarbon concentrations in sediments, both within a specific shoreline segment and among sites (Babcock et al. 1994, Harris et al. 1996), probably mitigated the negative effects of persistent shoreline oil on the foraging behavior of adult oystercatchers. All pairs that foraged on persistently oiled beaches also foraged on un-oiled beaches.

The presence of elevated hydrocarbon indices in the feces of chicks in 1993 provided direct evidence that some Black Oystercatchers were exposed to oil that persisted on shorelines of Prince William Sound. Hydrocarbon concentrations documented in sediments and mussels indicated that exposure was via a trophic pathway; no external oiling was observed on adults or chicks in all three years of study. Exposure of chicks to persistent shoreline oil was highest in Herring Bay, in Bay of Isles, and on northwestern Knight Island. Exposure to persistent shoreline oil was highly variable within these areas and minimal outside of these areas.

Any differences in breeding success between oystercatchers nesting along shorelines that were heavily oiled in 1989 and those that nested on un-oiled shorelines most likely were overridden by the effects of predation on eggs and young, mainly by Common Ravens. The ability of ravens to remember food caches is well known, and I suspect that ravens were the

cause of complete and rapid depredation of small (fewer than 20 nests) colonies of Arctic Terns (*Sterna paradisaea*) and Mew Gulls (*Larus canus*) on islets where oystercatchers nested. Although I was unable to detect an increased presence of ravens in areas of un-oiled shorelines on Knight Island that might account for lower productivity in these areas, the high mobility of ravens (adults were seen flying through mountain passes to connected bays) made the nests and young of many oystercatcher pairs susceptible to their predation. The effects of predation on breeding success of oystercatchers on Knight Island are further supported by the relationship of high productivity on Green Island, despite being oiled in 1989, and low raven abundance. Other than predator influences, shoreline features were similar between areas of persistently oiled and un-oiled shorelines on Knight Island, and environmental factors, including prey density and diversity, were not the cause of differences in productivity between persistently oiled and un-oiled groups.

Although reduced parental care and other reproductive impairments have been observed in marine birds that were experimentally dosed with oil, oystercatchers exhibited no dramatic behavioral or physiological (measured indirectly by egg volume, clutch size, and ability to re-nest) changes that were indicative of oil ingestion. The use of multiple foraging sites and the variety of available prey probably reduced the negative effects of occasionally ingesting oil-contaminated mussels, an option not available to individuals in dosing experiments.

Despite the lack of evidence of negative effects of oil ingestion on adults, oystercatcher chicks were affected by the presence of persistent shoreline oil in the territories where they were raised. Slower mass gain was evident in chicks raised on heavily oiled shorelines but did not correspond to sediment hydrocarbon concentrations at specific nest sites. The pronounced effect of oil ingestion on mass gain of chicks has been documented in other marine birds (Butler and Lukaszewicz 1979, Boersma et al. 1988). Differences in growth rates between oil-dosed and control chicks in these studies converged as chicks grew older, and dosing had little effect on the growth of appendages (bill and tarsi). The reduction in mass gain in oystercatcher chicks did not translate into re-

duced productivity. Similarly, masses of older chicks did not differ between oiling groups, suggesting that masses were similar by the time the chicks fledged. However, the fate of young birds after gaining independence from their parents is unknown; young oystercatchers are less-efficient foragers than adults for most of their first winter (Falxa 1992). Thus, the effects of persistent oil on recruitment are unknown. In addition, little information exists on long-term cumulative effects of oil ingestion in free-living birds that consistently occupy contaminated sites.

The restricted and local effects of persistent oil exposure on Black Oystercatchers are corroborated by the lack of any large-scale population changes in oystercatchers in the oiled area of Prince William Sound (Aglers et al. 1994). In addition, hydrocarbon concentrations in sediments underlying mussel beds decreased, on average, 37% between 1992 and 1993 (Babcock et al. 1996). Because oil released into the water by contaminated sediments provides little risk to surrounding unoiled shorelines (Babcock et al. 1994), further degradation of oystercatcher foraging habitat is not expected. Reoccupation of oiled habitats on Green Island (Andres 1997), and in other areas of Prince William Sound (Day et al. 1997), indicates that Black Oystercatchers can recover from major shoreline perturbations; however, daily disturbance can extirpate local populations of oystercatchers (see Andres 1996). Because persistent shoreline oil was patchily distributed and affected relatively few pairs of oystercatcher, two options exist for restoration of oiled mussel beds that would have a minimal effect on the Black Oystercatcher population: (1) allow persistent oil to slowly weather *in situ*, or (2) clean remaining oiled mussel beds. Either option would present little risk to the Black Oystercatchers that inhabit Prince William Sound.

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