IMMEDIATE IMPACT OF THE 'EXXON VALDEZ' OIL SPILL ON MARINE BIRDS

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ABSTRACT.—On 24 March 1989, the oil tanker 'Exxon Valdez' spilled 260,000 barrels of crude oil in Prince William Sound, Alaska. Oil eventually drifted over 30,000 km² of coastal and offshore waters occupied by approximately one million marine birds. More than 30,000 dead birds of 90 species were retrieved from polluted areas by 1 August 1989. Of those identified, murres (74%), other alcids (7.0%), and sea ducks (5.3%) suffered the highest mortality from oil, and most (88%) birds were killed outside of Prince William Sound. A colony of 129,000 murres at the Barren Islands was probably devastated. Another 7,000 birds were retrieved between 1 August and 13 October, but most of those birds appeared to have died from natural causes. This later die-off was composed largely of shearwaters and other procellariids (51%), gulls (22%), and puffins (14%). Based on aerial and ship-based surveys for populations at risk, and extrapolating from the number of dead birds recovered, we estimate that the total kill from oil pollution was from 100,000 to 300,000 birds. *Received 8 September 1989, accepted 27 December 1989.*

THE NORTHERN Gulf of Alaska, including Prince William Sound and Cook Inlet (Fig. 1), hosts some of the largest populations of marine birds in North America. Millions of pelagic seabirds, including fulmars, petrels, cormorants, kittiwakes, murres, and puffins, breed at major colonies on or near the Kenai and Alaska peninsulas and Kodiak Island (Bailey 1976, 1977; Sowls et al. 1978; Hatch and Hatch 1983). Millions of Short-tailed and Sooty shearwaters (*Puffinus tenuirostris* and *P. griseus*) migrate through the area in summer (Gould et al. 1982). Hundreds of thousands of coastal marine birds, including loons, grebes, sea ducks (e.g. scoters, eiders, Oldsquaw [*Clangula hyemalis*]) and murrelets, winter in Prince William Sound and sheltered bays throughout the area (Forsell and Gould 1981, DeGange and Sanger 1986).

On 24 March 1989, the oil tanker 'Exxon Valdez' went aground in Prince William Sound and spilled more than 260,000 barrels of Alaska North Slope crude oil. That constituted the largest oil spill in North America to date, and the largest spill ever to occur in an arctic environment. During the weeks that followed, currents and prevailing winds pushed oil out of Prince William Sound and into the Gulf of Alaska, where it eventually drifted 750 km to the southwest. Approximately one million marine birds occurred in the affected region. Initially, the oil formed a large fluid slick that coated all shorelines and wildlife in its path. Later, oil mixed with seawater to form a "mousse" emulsion and broke up into numerous smaller patches.

The magnitude of bird mortality after an oil spill depends on the size of local bird populations, their foraging behavior, whether populations are aggregated or dispersed at the time of the spill, and on the quantity of oil spilled and its persistence (NRC 1985). After contact, oil can kill birds by removing the insulative property of their feathers (causing hypothermia) and through toxicological effects after ingestion (Peakall et al. 1982, Fry and Lowenstine 1985). The most vulnerable birds include loons, grebes, sea ducks, and alcids because these species spend most of their time swimming on the sea surface and often aggregate in dense flocks.

We report here on the movement and distribution of oil following the 'Exxon Valdez' spill, marine bird populations at risk, and the number

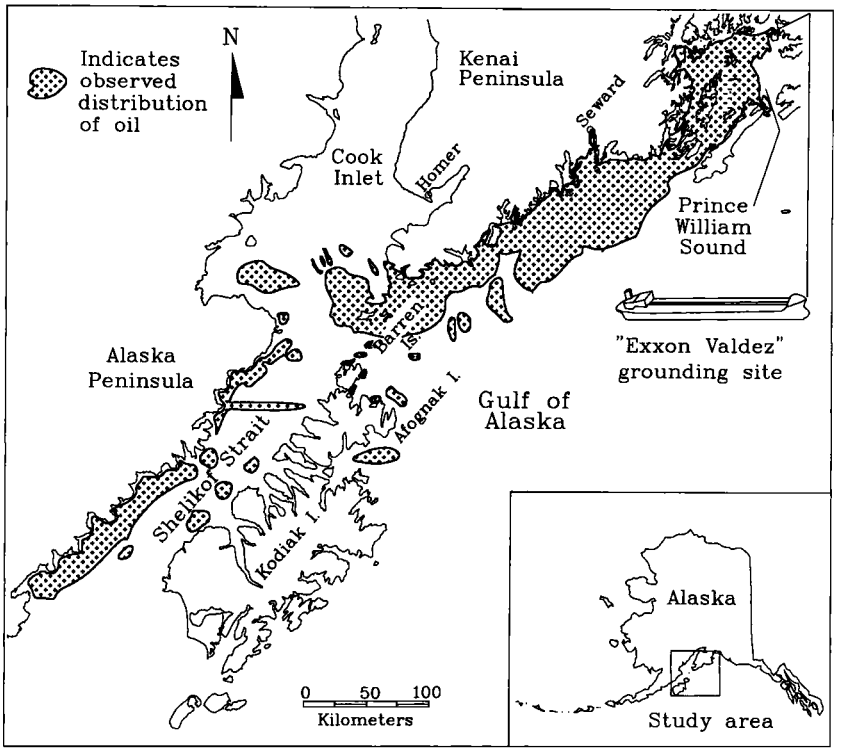

Fig. 1. Composite map of the distribution of 'Exxon Valdez' oil observed on aerial overflights between 24 March and 20 May, 1989. Absence of oil on map does not necessarily mean that oil did not occur in an area—only that it was not observed (e.g. due to weather constraints on flying or visibility).

and species composition of dead birds retrieved from the affected area. We speculate on the limits of total mortality.

METHODS

Dead birds were retrieved from shorelines and open waters in Prince William Sound, and along the Kenai Peninsula, Kodiak Island, and Alaska Peninsula, by fishermen under contract to Exxon Oil Company and personnel from the U.S. Fish and Wildlife Service (USFWS), Alaska Department of Fish and Game, National Parks Service, Alaska Department of Environmental Conservation (ADEC), and the International Bird Rescue Center. Corpses were identified (Ainley et al. 1980) and processed by USFWS and Minerals Management Service personnel at receiving centers in Valdez, Seward, Homer, and the town of Kodiak between 25 March and 13 October, 1989. Numbers of dead birds were grouped for illustrative purposes (Fig. 2) according to their proximity to major islands or bays. Only birds retrieved before 1 August, and birds after 1 August known to be oiled, were included in Figure 2.

Assessments of species and populations at risk are based on historical surveys (Dwyer et al. 1975; Bailey 1976, 1977; Sowls et al. 1978; Manuwal 1980; Forsell and Gould 1981; Gould et al. 1982; Hogan and Murk 1982; Hatch and Hatch 1983; Nishimoto and Rice 1987), and on aerial and boat-based surveys of the affected area initiated by the USFWS after the spill. An aerial survey of all shoreline habitats in Prince William Sound, using methods described by Hogan and Murk (1982), was begun on 28 March 1989 and completed by 1 April. Shoreline habitats in the sound that became oiled after the first survey (Fig. 1), and adjacent un-oiled shorelines, were resurveyed on 8 April. Nearby shorelines were surveyed for a third time on 20 April. An aerial survey of all shoreline habitats on the Kenai Peninsula from the western edge of Prince William Sound to Homer, including the Barren Islands, was completed on 6 April. An aerial survey (456 km) of waters ≤40 km south of the Kenai Peninsula, consisting of seven parallel north-south transects from Prince William Sound to the Barren Islands, was completed on 29 April. Correction factors were applied to aerial survey bird counts to adjust for visibility bias of different species (W. Butler unpubl. data). Ship-based surveys (408 ten-min transects) were conducted south of the Kenai Peninsula, in lower

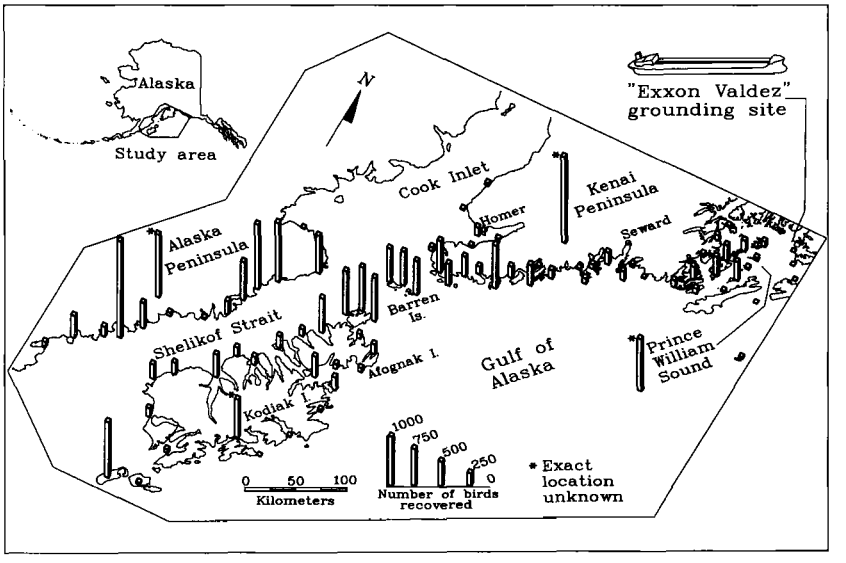

Fig. 2. Distribution and abundance of dead birds retrieved from areas affected by the 'Exxon Valdez' oil spill. Bars with asterisks indicate the number of birds retrieved from regions (e.g. Prince William Sound) without specific information on where they were found. Figure includes only those birds recovered before 1 August 1989 (see Table 1).

Cook Inlet, and in Shelikof Strait from the USFWS vessel 'Tiglax' between 1 and 7 May 1989 using a standard protocol for counting birds at sea (Gould et al. 1982).

Historical data on the distribution and abundance of marine birds in the Gulf of Alaska were collected between 1975 and 1986 as part of the Outer Continental Shelf Environmental Assessment Program (OCSEAP). Data collected in the months of March, April, and May were used to estimate numbers of marine birds at risk in a 30,052 km^2 area delimited by the farthest extent of oiling observed in the Gulf of Alaska. Mean bird densities were calculated for 30' latitude-longitude blocks, and numbers of birds within a polygon defined by the spill were estimated using CAMRIS (Computer Aided Mapping and Resource Inventory System, Ecological Consulting Inc., Oregon). Survey data were available for 76% of blocks enclosed or intersected by the perimeter of the spill zone.

A corpse drift experiment was initiated on 6 May 1989 by releasing 100 tagged seabird carcasses into the water 10 km northeast of the Barren Islands. The heavily oiled carcasses (89 murres, 6 murrelets, 2 guillemots, 1 scoter, 1 cormorant, and 1 kittiwake) were obtained 1-3 days earlier from beaches on the Alaska Peninsula. Birds were tagged with notecards encased in plastic and attached to a leg with nylon string.

The movement of oil was monitored on more than 300 aerial surveys by the Alaska Department of Environmental Conservation and the National Oceanic and Atmospheric Administration (NOAA). Maps of oil distribution were updated regularly at ADEC headquarters in Valdez (by Kendziorek). We used overflight observations made until 20 May 1989 to generate our composite map (Fig. 1). Weather information was provided by NOAA and the U.S. Coast Guard. Information on ocean currents in the northern Gulf of Alaska was obtained from Schumacher and Reed (1980) and Royer (1981).

Results

Prince William Sound.—The 'Exxon Valdez' grounded and began leaking oil in the northeastern corner of Prince William Sound shortly after midnight on 24 March 1989. Prevailing currents and light to moderate northeast winds on 24-26 March, and strong northeast winds on 27-28 March, pushed oil rapidly through and out of the southwestern corner of the sound (Fig. 1). The slick engulfed several small islands and portions of larger islands in its path. During this phase, the oil remained fluid, and coated shorelines and birds with a smooth and liquid layer.

Approximately 54,000 live birds were counted along the entire shoreline (coast and islands) of Prince William Sound during aerial surveys conducted between 28 March and 1 April, 1989.

Half were in the area affected by oil. Similar species and numbers (44,000) were found on comparable aerial surveys conducted in 1971 (Hogan and Murk 1982). However, bird numbers are generally underestimated on aerial surveys (Bajzak and Piatt 1990), and our aerial surveys covered little open-water habitat in Prince William Sound. Therefore, boat-based surveys of both shoreline and open-water habitats of the sound in 1972–1973 (Dwyer et al. 1975) provide a better indication of species and populations at risk at the time of the spill. Boat-based shoreline surveys conducted in 1984–1985 (Irons et al. 1988) corroborate the surveys of Dwyer et al. (1975). The majority of birds (346,000 ± 58,000) observed in spring on boat-based surveys were sea ducks (37.2%), gulls (25.2%), cormorants (6.4%), murrelets (6.3%), grebes (3.3%), murres (1.8%), loons (1.4%), and guillemots (1.2%). On all surveys, bird populations were dispersed throughout Prince William Sound, although gulls and sea ducks (other than Harlequin Ducks, *Histrionicus histrionicus*) were concentrated at the heads of bays and inlets.

Approximately 3,400 birds were retrieved from areas engulfed by oil in Prince William Sound (Fig. 2). Most carcasses were completely coated by oil. Although the first dead, oiled birds were retrieved from near the spill site (Bligh Island) on 25 March 1989, it took several days for the oil to affect bird populations to the southwest, and several more days for investigators to mount a search of remote shorelines. Hundreds of birds were recovered weekly over the period 5 April to 6 June, but after 6 June only 64 decomposed birds were retrieved from Prince William Sound.

The species composition of dead birds (Table 1) was different than the composition of populations at risk (above). Proportionately fewer gulls and sea ducks, and proportionately more loons, grebes, cormorants, murres, and murrelets, were killed by oil than were present in the sound. We saw Bald Eagles (*Haliaeetus leucocephalus*) scavenge dead and dying oiled birds, and many of the 32 eagle carcasses returned to Valdez were oiled. Although we also saw gulls scavenge carcasses, and we saw hundreds of gulls with oiled plumage, relatively few were found dead.

Between one precontact (28–30 March 1989) and two postcontact (8 and 20 April) aerial surveys around heavily oiled islands, local populations of loons, grebes, cormorants, and sea ducks declined by 44–84%, whereas those of gulls and eagles increased by 87–240%. In unoiled bays and inlets of the affected area, all species increased in abundance (24–340%), except for Bald Eagles, which declined by 21% on the second postspill survey.

Kenai Peninsula.—Between 31 March and 6 April, approximately 2 million gallons of oil escaped from Prince William Sound into the Gulf of Alaska. Oil was entrained in the Alaska Coastal Current and, aided by moderate north and northeast winds, spread to the west but remained 20–30 km offshore of the south coast of the Kenai Peninsula. Between 7 and 9 April, light to moderate south and southwest winds pushed oil north to engulf offshore islands, capes, and headlands along the full length of the south Kenai Peninsula (Fig. 1). In the early part of this phase, oil remained liquid and formed a nearly continuous slick. Later, oil began to emulsify, and the slick broke up into several large patches.

At least 36,250 birds occupied coastal habitats of the southeastern Kenai Peninsula (east from Gore Point) during a precontact aerial survey conducted on 6 April. Historical surveys (Bailey 1977, Sowls et al. 1978) recorded ca. 116,000 seabirds at colonies in the same region during summer. Postcontact aerial surveys conducted on 29 April revealed densities of ca. 10 birds/km^2 in offshore waters up to 40 km south of the Kenai Peninsula.

Sea ducks (41.9% of all coastal birds) were abundant near shore, and murres (mostly Common Murres, *Uria aalge*) were numerically important species in both coastal (34.1%) and offshore (19.5%) waters. Gulls (21.9%) and cormorants (6.0%) were common inshore, whereas procellariids (13.4%), gulls (14.8%), phalaropes (11.4%), and other pelagic species predominated offshore. Approximately 28,000 Common Murres breed at three colonies on the southeast Kenai Peninsula (Sowls et al. 1978), and murres were observed attending these colonies by 9 April (precontact). Although tens of thousands of Tufted and Horned puffins (*Fratercula cirrhata* and *F. corniculata*) breed at colonies along the coast (Sowls et al. 1978, Nishimoto and Rice 1987), they evidently did not arrive in the area much before 29 April, when Tufted Puffins made up 16.6% of birds observed offshore.

TABLE 1. Proportions (%) and total numbers of birds retrieved from Prince William Sound (PWS), Kenai Peninsula (KP), Barren Islands (BI), Kodiak (KOD), and the Alaska Peninsula (AP) between 25 March and 13 October, 1989.

Species group	Area					Total before 1 Aug[a]	Total after 1 Aug
	PWS	KP	BI	AP	KOD		
Loons	8.7	1.8	0.3	0.4	<0.1	1.5	<0.1
Grebes	11.8	1.6	0.2	0.3	0.1	1.7	<0.1
Procellariids	0.4	4.8	0.7	1.1	4.9	2.9	50.7
Cormorants	16.0	4.3	0.4	0.6	0.7	3.0	1.0
Sea ducks	24.9	8.4	0.7	1.6	0.7	5.3	0.3
Gulls	1.8	5.5	0.5	1.2	2.4	2.4	21.6
Murres	15.2	58.1	88.3	89.0	84.6	73.7	7.1
Murrelets[b]	11.6	4.9	3.7	0.6	0.5	2.2	2.0
Guillemots	4.7	4.6	1.2	1.6	0.8	2.2	0.4
Puffins	0.0	1.5	0.2	0.2	1.4	0.9	13.8
Other alcids	0.8	1.6	3.6	3.3	2.9	1.7	1.7
Other birds	4.1	2.9	0.7	0.1	0.9	2.5	1.3
Total numbers							
Retrieved	3,358	6,225	2,163	8,881	8,548	29,175	6,940
Identified	2,882	5,174	1,922	8,691	8,200	26,869	6,238

[a] Includes 167 old carcasses that were oiled and apparently killed before 1 August, but retrieved after 1 August. Total does not include 31 oiled birds found on Middleton Island and 1,091 birds that died at oiled-bird rehabilitation centers.

[b] *Brachyramphus* murrelets only.

Approximately 6,200 birds were found dead on shorelines or floating in the water along the Kenai Peninsula between 12 April and 1 August (Fig. 2). At least 31 dead, oiled birds were retrieved from Middleton Island, ca. 150 km south of Prince William Sound. After 1 August, most of the 664 birds recovered along the Kenai Peninsula were not oiled and appeared to have died from natural causes (see below).

As in Prince William Sound, the species composition of birds recovered from the Kenai Peninsula (Table 1) was different from the composition of populations at risk (above). More diving species than aerial species were killed. In contrast to Prince William Sound, there was a marked decrease in the proportions of loons, grebes, cormorants, and sea ducks killed along the Kenai Peninsula, and an increase in the proportions of murres and procellariids (mostly shearwaters) killed.

Barren Islands.—On 10-11 April, a storm in the Gulf of Alaska generated strong northeast winds that dispersed and emulsified the oil. During a period of variable light winds between 12 and 16 April, oil reached the southwestern tip of the Kenai Peninsula, where currents moved it north into Cook Inlet and southwest toward the Barren Islands. Another period of moderate south winds between 17 and 21 April pushed oil into bays and fjords along the Kenai coast, and drove more oil north into Cook Inlet. Oil lingered in a large area surrounding the Barren Islands and became more weathered and emulsified into "mousse" toward the end of this phase.

Aerial surveys (6 April) indicated that before oil contamination, at least 21,000 marine birds (mostly sea ducks, gulls, and murres) were present along the southwestern Kenai coast (west of Gore Point), and 123,600 birds (79% murres, 20% gulls) occurred near the Barren Islands. Historical surveys indicated that ca. 13,000 seabirds (mostly puffins and Black-legged Kittiwakes [*Rissa tridactyla*]) breed in colonies along this portion of the Kenai coast, whereas much larger populations (150,000 Fork-tailed Storm-Petrels [*Oceanodroma furcata*], 135,400 puffins, 118,000 Common Murres, 11,000 Thick-billed Murres [*Uria lomvia*], and 46,600 kittiwakes) breed at the Barren Islands (Bailey 1976, Manuwal 1980). Coastal and offshore waters around the southwestern Kenai Peninsula and the Barren Islands usually support high densities of marine birds in spring (Bailey 1976, Gould et al. 1982). When oil reached this area, it appears that few puffins had arrived at colonies, whereas murres were gathered in large prebreeding aggregations (Tuck 1961) around the Barren Islands.

Of the 6,200 birds retrieved from the Kenai

Peninsula, most came from the southwestern tip (Fig. 2). An additional 2,163 birds (mostly murres) were retrieved from the Barren Islands (Table 1) between 14 April and 22 August (only 22 birds after 26 May). Ship-based (2 May) and aerial (29 April) surveys conducted near the Barren Islands after oil exposure revealed no large aggregations of murres. However, a flock of ca. 25,000 murres was observed offshore from one of the islands on 22 May (Bailey 1989). Murre densities (1.4 birds/km^2) were lower on post-contact ship-based surveys near the Barren Islands than in any other area surveyed from the south Kenai Peninsula (9.9 murres/km^2) to the Alaska Peninsula (20.6 murres/km^2). Census data obtained in summer 1989 indicates that murre attendance at colonies on the Barren Islands was 62% lower in 1989 than in 1979.

Kodiak and the Alaska Peninsula.—Between 22 and 28 April 1989, moderate to strong southeast winds limited oil tracking surveys in lower Cook Inlet and Shelikof Strait. However, it was apparent that winds and prevailing currents drove oil into Shelikof Strait during this period because aerial surveys on 28 April found mousse concentrations along 300 km of the Alaska Peninsula (Fig. 1). In subsequent aerial and shoreline surveys, oil mousse had washed up on beaches throughout the area, sometimes in thick mats which blanketed large portions of the shoreline. On 8–9 May, strong northwest winds drove mousse southeast across Shelikof Strait and deposited it on western shorelines of Kodiak and Afognak islands.

Post-spill (3–6 May) ship-based surveys revealed densities of 28.4 birds/km^2 along the coast of the Alaska Peninsula, 14.6 birds/km^2 in Shelikof Strait, and 65.4 birds/km^2 near the Semidi Islands (ca. 120 km southwest of Kodiak Island). Extrapolating from areas (Gould et al. 1982) of ca. 7,000 km^2 along the coast (<200 m depth) and 6,600 km^2 in the strait, ca. 295,000 birds occupied Shelikof Strait. Again, murres dominated (65%) among species observed, followed by procellariids (15.4%, mostly Northern Fulmars [*Fulmarus glacialis*]), and Glaucous-winged Gulls (4.4%, *Larus glaucescens*). Sowls et al. (1978) recorded 308,000 seabirds breeding at colonies along the eastern Alaska Peninsula and 38,615 seabirds on Afognak Island. Predominant species included murres, Tufted Puffins, gulls, and kittiwakes. In addition to seabirds, several hundred thousand sea ducks (mostly Oldsquaw, scoters, eiders, and Harlequin Ducks) winter in coastal habitats of the Kodiak Archipelago and Alaska Peninsula (Forsell and Gould 1981).

A total of 17,429 birds were found dead on beaches of the Alaska Peninsula and the Kodiak Archipelago before 1 August (Table 1, Fig. 2). The proportion of murres among the birds recovered was higher than in other regions. Only 6 of 802 birds we examined on 3–5 May were fresh kills; the rest were old, mousse-coated carcasses deposited in greatest numbers where mousse was concentrated on beaches. It appeared that birds and mousse had drifted together. An additional 6,199 birds were recovered after 1 August, but most apparently died of natural causes (see below).

Three of 100 tagged carcasses released on 6 May northeast of the Barren Islands were recovered 240 km southwest on the Alaska Peninsula 12, 30, and 55 days later. All three carcasses (murres) were recovered on the same beaches (in Puale Bay) from which they had been retrieved before tagging.

Mortality of birds during summer and autumn.—In June and July, small patches of mousse, sheen, and tar balls were observed at sea as far southwest as the Shumagin Islands (ca. 400 km southwest of Kodiak) and throughout the entire contaminated area. However, no large oil patches were observed at sea after May. It appeared that relatively few birds were killed by oil after May because recoveries of affected species diminished greatly in June and July (Fig. 3, note that processing lagged mortality by several weeks in the early stages of the spill).

During August and September, hundreds of seabirds were recovered weekly on Kodiak Island and along the Alaska and Kenai peninsulas (Fig. 3). Some of these recoveries (totaling 6,940) were old, decomposed birds that were probably killed by oil in April and May (e.g. 702 unidentifiable sea ducks and 440 murres), but most had died more recently. The die-off contained chiefly surface-feeding species that were little affected by oil in April and May (e.g. 2,751 shearwaters, 331 storm-petrels, 362 *Larus* gulls, and 984 Black-legged Kittiwakes). Most of the 863 puffins recovered were recently fledged young (Sanger 1989). Field observations (D. Zwieflehofer and G. Sanger pers. comm.) and preliminary results of necropsies and contaminant analyses (E. Robinson-Wilson and T. Early pers. comm.) indicated probable death from starvation (no fat, low body mass, empty stom-

achs) rather than from oil contamination (no trace of external oil or internal hydrocarbon residues).

Populations at risk in the entire spill zone.—We estimated populations at risk from three independent data sources.

1. In aerial and boat-based surveys conducted after the spill (discussed above), at least 585,000 marine birds were present in the region from Prince William Sound to south of Shelikof Strait. From that total, we subtracted those species that were only slightly affected by oil (125,000 fulmars, petrels, dabbling ducks, gulls, kittiwakes, puffins, etc.), and added ca. 200,000 sea ducks that winter in coastal areas of Kodiak and the Alaska Peninsula (Forsell and Gould 1981). We estimate that 660,000 birds of high-risk species were in the region. Oil slicks covered approximately half of this region. Therefore, ca. 330,000 marine birds with high vulnerability to oil were in areas heavily polluted by oil.

2. Using historical OCSEAP data on marine bird densities in the Gulf, we estimated that 982,600 marine birds were in a 30,052 km^2 area circumscribed by the spill perimeter outside of Prince William Sound. However, procellariids (51.4%), gulls (12.3%), and puffins (8.5%) accounted for most of that total. Approximately 273,000 birds were at high risk (0.7% loons, 0.2% grebes, 6.1% cormorants, 16% sea ducks, 71% murres, 4.1% murrelets, and 1.8% guillemots). Combined with historical data from Prince William Sound (Dwyer et al. 1975), the latter estimate indicates that 370,600 birds of high-risk species were in the oil-impact zone.

3. Most of the birds affected were colonial seabirds, and historical colony census data obtained during summer months (Sowls et al. 1978) can be used to estimate seabird populations at risk in spring 1989 because many species (e.g. murres) were observed attending colonies during the weeks immediately following the spill. Approximately 878,000 seabirds breed at colonies directly affected by the spill. We subtracted the numbers of low-risk species to estimate that 283,000 seabirds (of which 243,000 were Common Murres) were at high risk.

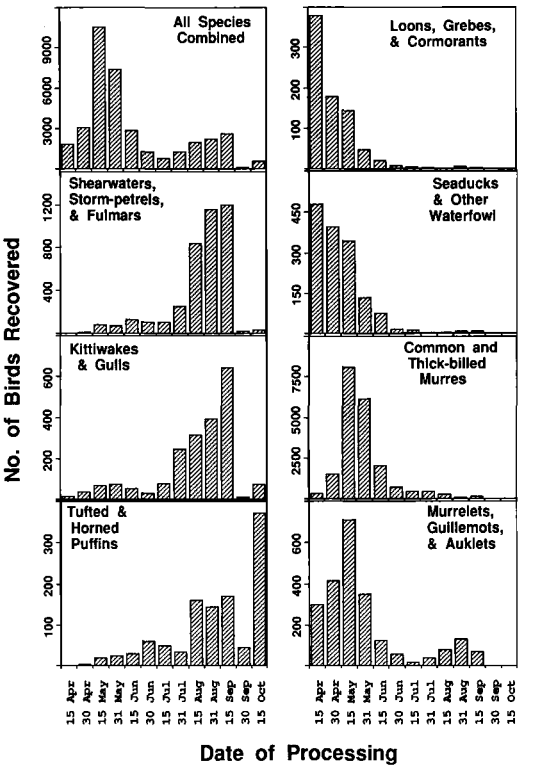

Fig. 3. Numbers of different bird taxa recovered and processed at USFWS receiving centers from April to October, 1989. Note that processing dates usually lagged recovery dates by 1–3 weeks, and that recovery dates lagged mortality by 0–4 weeks. Dates of processing given on the *x*-axis include the 2-week interval preceding the date shown.

Discussion

Bird recoveries.—Between 25 March and 1 August, ca. 30,000 oiled birds were retrieved from the entire affected area. However, it is likely that some of these birds died of natural causes and were exposed to oil while on beaches or floating at sea (Ford et al. 1987). Of 1,888 birds brought to oiled-bird rehabilitation centers, 1,091 died, and the remainder were treated and released. Field observations, videotape recordings, and anecdotal reports also indicate that several thousand oiled birds are unaccounted for in our analysis because they were buried, burned, or lost during beach-cleaning and oil-skimming operations. Thus it is impossible to determine the exact number of birds that were killed by 'Exxon Valdez' oil and later found, but we conclude that 30,000 is a minimum number.

Most birds retrieved after 1 August were unoiled individuals of surface-feeding species that apparently died of starvation. The observed mortality was similar to a seabird die-off that occurred in Gulf of Alaska and Bering Sea waters

in 1983 (Nysewander and Trapp 1984, Lobkov 1986). In that event, tens of thousands of adult shearwaters, kittiwakes, and other seabirds died of starvation during the months of August and September, and kittiwakes exhibited near-total breeding failure throughout their range in Alaska (Hatch 1987). Widespread breeding failure of kittiwakes has occurred in other years before and after 1983, including 1989 (pers. obs., S. Hatch and A. L. Sowls pers. comm.). Thus, neither the kittiwake breeding failure nor the die-off of adult seabirds and young observed in August and September 1989 should be confused with the known effects of the oil spill.

Most birds (88%) killed by oil were retrieved outside of Prince William Sound. We conclude that the distribution and species composition of birds recovered in the Gulf of Alaska were largely determined by the diminished lethal effects of oil after late April (when oil emulsified into mousse), and by the likelihood that most birds found on Alaska Peninsula and Kodiak Island beaches before 1 August were killed near the Barren Islands and southwestern Kenai Peninsula in April and drifted subsequently with mousse patches to the beaches on which they were found.

Several lines of evidence support our conclusions. First, there was little difference in the species composition of birds retrieved from the Barren Islands, Alaska Peninsula, and Kodiak Archipelago despite major differences in composition of local avifauna (e.g. approximately 100 times more murres and 10 times fewer cormorants breed on the Barren Islands than on the Kodiak Archipelago). Second, if significant oil mortality had occurred after April, we would have observed far more cormorants and puffins among recoveries in the Gulf because they were abundant and vulnerable in May through July. Third, most bird carcasses recovered from Alaska Peninsula and Kodiak Island beaches were decomposed. Presumably they had died some weeks before and drifted to those beaches. Carcasses dropped at the Barren Islands in our drift experiment were all recovered weeks later on the Alaska Peninsula. Finally, 60% of all dead birds were recovered from Kodiak Island and the Alaska Peninsula before 1 August, but only 8% of all live birds were recovered there by that date.

Estimated total losses.—The number of birds recovered on beaches after an oil spill represents a fraction of the actual mortality (Ford et al. 1987). Once killed at sea, birds may drift away from coasts and never wash ashore, sink before reaching shore, wash up on inaccessible shorelines and not be discovered, wash up on accessible beaches but get buried or scavenged before discovery, or wash up on a beach but be overlooked (e.g. because of small size or encasement in heavy oil). If search effort and all the above variables were quantified, it would be possible to calculate accurately the number of birds killed at sea from the number recovered on beaches. Although we presently lack estimates for most variables, we can make a preliminary assessment based on data obtained after this spill and from other studies.

It is known from drift experiments conducted elsewhere (Coulson et al. 1968; Hope-Jones et al. 1970, 1978; Bibby and Lloyd 1977; Bibby 1981; Page et al. 1982; Threlfall and Piatt 1983) that relatively few (e.g. 0–59%) birds killed at sea ever reach shore. Experiments with crude-oil saturated seabirds (Burger 1989) indicated that many oiled carcasses sink in salt water, and buoyancy decreases with time (21% of heavily oiled alcid carcasses sank 21–25 days after oiling, 44% after 25–35 days, and 63% after 50–60 days). Freshly oiled alcid corpses may sink at rates of ca. 15% per day (Ford et al. 1987). Wind speed, its direction relative to land, and ocean currents are additional factors that determine the proportion of birds deposited on beaches. In the Gulf of Alaska, prevailing winds between 1 April and 15 May usually (22 of 35 days) had a northerly component that undoubtedly pushed many carcasses away from land. Conversely, the Alaska Coastal Current carried corpses in a southwesterly direction toward the Alaska Peninsula.

The value of our corpse drift experiment was limited by several factors. We delayed releasing any oiled carcasses until 6 weeks after the spill because of concern for Bald Eagles and other scavengers. Furthermore, we used old carcasses retrieved from beaches, and search effort in the Gulf diminished after May. Thus, the actual corpse recovery rate in the Gulf must have been considerably higher than the 3% we observed in our drift experiment.

Outside of Prince William Sound, logistics and geography precluded a thorough and repetitive search of affected coastlines. Only accessible beaches were surveyed systematically, and even those were checked so infrequently that many beached birds must have disappeared before they could be recovered. On the Barren Islands, repeated surveys of two beaches in ear-

ly May indicated that carcasses were disappearing at rates of 16–20% per day (Bailey 1989, Jones 1989). Other studies indicate disappearance rates of 3–40% per day depending on wave intensity and tide ranges between surveys (Ford et al. 1987, Burger 1989).

Based on the above considerations, we estimate tentatively that the number of oiled birds recovered represents only 10–30% of the actual kill, which was probably between 100,000 and 300,000 birds. Three independent estimates indicated that between 283,000 and 370,000 marine birds were at high risk in the spill zone, but we know from post-spill surveys that they were not completely eliminated and high-risk species were relatively abundant in Shelikof Strait after the spill. Thus, our estimates of birds killed and birds at high risk are of the same order of magnitude. However, population estimates based on aerial and boat-based surveys represent static counts of bird abundance and do not account for the flux of birds in and out of census areas (Ford et al. 1987). Thus, the number of birds at risk might have been larger than we calculated and post-spill counts may have been biased upwards.

Population effects.—The alcids suffered the greatest losses, as they usually do when oil is spilled in arctic or boreal waters (NRC 1985). Perhaps 10% of the existing Gulf of Alaska population of Common Murres and >50% of the population at the Barren Islands were killed. To put those losses in perspective, it should be noted that the total Alaskan population of Common Murres exceeds 5 million birds (Sowls et al. 1978), and it is not unusual for tens or hundreds of thousands of murres to die *en masse* from natural causes (Tuck 1961, Bailey and Davenport 1972) or chronic oil pollution (McKnight and Knoder 1979, Piatt et al. 1985). Thus, although local populations may have been seriously reduced, it may prove difficult to identify sources of population variability beyond the first year (Stowe 1982, Dunnet 1987). Populations should fully recover in 20–70 yr, or sooner if birds emigrate from unaffected colonies (Ford et al. 1982, Samuels and Lanfear 1982).

Local populations of Pigeon Guillemots (*Cepphus columba*) and Marbled Murrelets (*Brachyramphus marmoratus*) were also decimated by the spill, but Gulf populations may be in the low hundreds of thousands (Sowls et al. 1978). Puffins appear to have avoided serious losses because they did not return to colonies until after the oil had passed. Nonalcid species that may have suffered high losses relative to the size of local populations included Yellow-billed Loons (*Gavia adamsii*), Pelagic Cormorants (*Phalacrocorax pelagicus*), Harlequin Ducks, and Bald Eagles.

Bird mortality following the 'Exxon Valdez' oil spill represents an unprecedented toll of marine birds from acute oil pollution (Piatt and Lensink 1989). The magnitude of losses was predictable given the size and species composition of marine bird populations in the region (Lensink 1984). Losses could have been much greater if the spill had occurred in summer or autumn. The immediate effect of the spill was to reduce the size of some local breeding bird populations in 1989, and that effect will persist as both production and recruitment are diminished for the future (Ford et al. 1982). For birds that survived oiling but ingested oil, or whose nest sites were contaminated, breeding success may have been reduced in the 1989 and future breeding seasons (Clark 1984, Fry et al. 1986). Long-term effects of the spill on marine birds are subject to continuing investigation by the U.S. Fish and Wildlife Service and other agencies.

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