Effects of oil pollution on seabirds in the northeast Pacific

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Abstract

This paper reviews the sources and impacts of oil pollution affecting seabirds in the eastern North Pacific. The numbers and volume of oil spills in this region increased markedly between 1974 and 1989. Spills that killed significant numbers of seabirds are reviewed. Beached bird surveys have demonstrated that small-volume, chronic oil pollution is an ongoing source of mortality in coastal regions. Experiments and models used in the North Pacific show that ocean currents, wind, seabird distribution, and the persistence of oiled carcasses at sea and ashore can all affect the assessments of mortality from major spills. Experimental releases of carcasses and drift-blocks at sea indicate that few birds killed by spills are likely to come ashore. Effects of oil on the plumage and physiology of birds are reviewed. Oil is known to affect thermoregulation, the alimentary system, blood, salt glands, osmoregulation, adrenal glands, kidneys, liver, the immune system, and reproductive performance, and can also produce mutations. The long-term efficacy of rehabilitation programs is reviewed and suggestions for future research are made.

Résumé

Les auteurs examinent les sources de la pollution par les hydrocarbures et ses effets sur les oiseaux marins, dans la région est du Pacifique Nord. Entre 1974 et 1989, le nombre de déversements d'hydrocarbures et le volume des hydrocarbures ainsi déversés ont beaucoup augmenté dans cette région. Les auteurs s'arrêtent sur les déversements qui ont décimé de fortes populations d'oiseaux marins. Les relevés des oiseaux échoués ont démontré que la pollution chronique par de faibles volumes d'hydrocarbures est une cause constante de mortalité dans les régions côtières. Les essais et les modèles réalisés dans le Pacifique Nord montrent que les courants océaniques, le vent, la distribution géographique des oiseaux marins et la présence continue des carcasses mazoutées, en mer et sur le rivage, sont autant de facteurs susceptibles d'influer sur la mesure de la mortalité attribuable aux déversements majeurs. Les rejets expérimentaux de carcasses et de blocs erratiques en mer indiquent un faible taux d'échouage des oiseaux tués par les déversements. Les auteurs examinent les effets des hydrocarbures sur le plumage et la physiologie des oiseaux marins. On sait que les hydrocarbures affectent la thermorégulation, l'appareil digestif, le sang, les glandes nasales, l'osmorégulation, les glandes surrénales, les reins, le foie, le système immunitaire et la capacité de reproduction. Les hydrocarbures peuvent également produire des variations idiotypiques. Les auteurs examinent l'efficacité à long terme des mesures correctives et suggèrent les domaines de recherche à approfondir.

1. Introduction

Oil is one of the most ubiquitous forms of pollution in the ocean, and seabirds are usually the most conspicuous and severely affected victims. Until recently, most of the North Pacific was spared the chronic and catastrophic oil pollution typical in the North Atlantic and Mediterranean and along the major oil shipping routes around Africa. The increasing industrialization of the Pacific Rim, coupled with major oil developments, such as the Alaska North Slope, have resulted in an increase in shipments of petroleum and a concomitant increase in accidental spills. Recent spills affecting California, Washington, British Columbia, and Alaska have received widespread public attention, and diverted funding to the study of the effects of oil on seabirds.

Oil at sea is a threat to seabirds because of its properties of forming a thin liquid layer on the water surface. The hydrophobic nature of petroleum hydrocarbons makes them interactive with the hydrophobic properties of bird feathers. Oil causes marked loss of insulation, waterproofing, and buoyancy in the plumage. In addition, petroleum oils contain many toxic compounds which can have fatal or debilitating effects on birds.

This review considers the following: sources of oil pollution; the effects of oil on seabirds (individuals and populations); the difficulties in assessing the impacts of catastrophic large spills and chronic small spills; the effectiveness of rehabilitation programs; and the research needed to address important issues. Most of our examples come from Alaska through California.

2. Types and sources of oil affecting seabirds

Crude oil is the most frequent cargo carried by large tankers. In the eastern North Pacific the bulk is Alaskan North Slope crude, but "heavy" crudes from the San Joaquin Valley and from offshore platforms off southern California are also transported along the coast. Accidents involving tankers (e.g., *Exxon Valdez*) are the greatest risk of spills of crude oil. Pipeline and platform spills have not been common in the North Pacific, with only one major spill from a platform (near Santa Barbara in 1969; Kolpack 1971) and one from an onshore production facility (San Francisco Bay in 1988; Fischel and Robilliard 1991), causing the deaths of a few hundred to a thousand birds. In the North Sea and Gulf of Mexico, where platforms are more common, spills are rare, but have been extremely devastating (e.g., *Ixtoc I* blowout in the Gulf of Mexico in 1979; National Research Council 1985).

Natural seeps are another source of crude oil, and occur at several shallow, coastal sites off southern California and Alaska. Their discharges are variable, usually only a few to dozens of barrels a day, and are most often detected as localized sheens or slicks. Varoujean (1983) found that resident birds appeared to avoid this oil, whereas migratory seabirds showed little avoidance behaviour.

Bunker fuel (number 6 fuel oil) is a mixture of tarry oil produced as a residual of refining processes, mixed with lighter, more volatile oils. Bunker oil is the predominant boiler fuel carried by commercial ships and used in pulp mills and other industries.

Smaller fishing and pleasure vessels are powered by lighter, more volatile diesel fuel (number 2 fuel oil) or gasoline. These fuels are chronically spilled in small volumes at marinas and fuelling stations. They are highly volatile and therefore pose less long-term risk to seabirds.

Vegetable and fish oils are sometimes spilled during transport or loading. These oils are not toxic, but external fouling can kill seabirds (McKelvey et al. 1980; Speich and Wahl 1986; Ambrose 1990).

3. Oil pollution in the North Pacific

3.1. Significant spills in the North Pacific

Cohen and Aylesworth (1990) reviewed data on spills of 1000 barrels (140 t) or greater collected by the U.S. Minerals Management Service for U.S. waters. Between 1974 and 1989 there were 67 of these large spills in the Atlantic, excluding the Gulf of Mexico, and 28 in the Pacific, including Hawaii and Alaska. These totalled 676 000 (average 45 000 per year) and 532 000 barrels (35 000 per year), respectively. When plotted in five-year intervals, these data show a trend of increasing numbers of spills, and total volume spilled, in the Pacific (Fig. 1). The *Exxon Valdez* spill represents 63% of the total spilled between 1984 and 1989 in Pacific waters. These data reflect the increasing volumes of shipping in the North Pacific and flow of Alaskan North Slope crude to southern markets.

All of these spills probably killed some birds, but this was documented in remarkably few cases. Estimates of seabird mortality resulting from oil spills in the eastern North Pacific are given in Table 1. In some cases (*Puerto Rican*, *Apex Houston*, *Nestucca*, and *Exxon Valdez*) the estimates were based on detailed field observations and the application of experiments and models to estimate the disappearance of oiled carcasses (Ford et al. 1987, 1991; Page et al. 1990; Piatt et al. 1990; Burger 1990, 1991a).

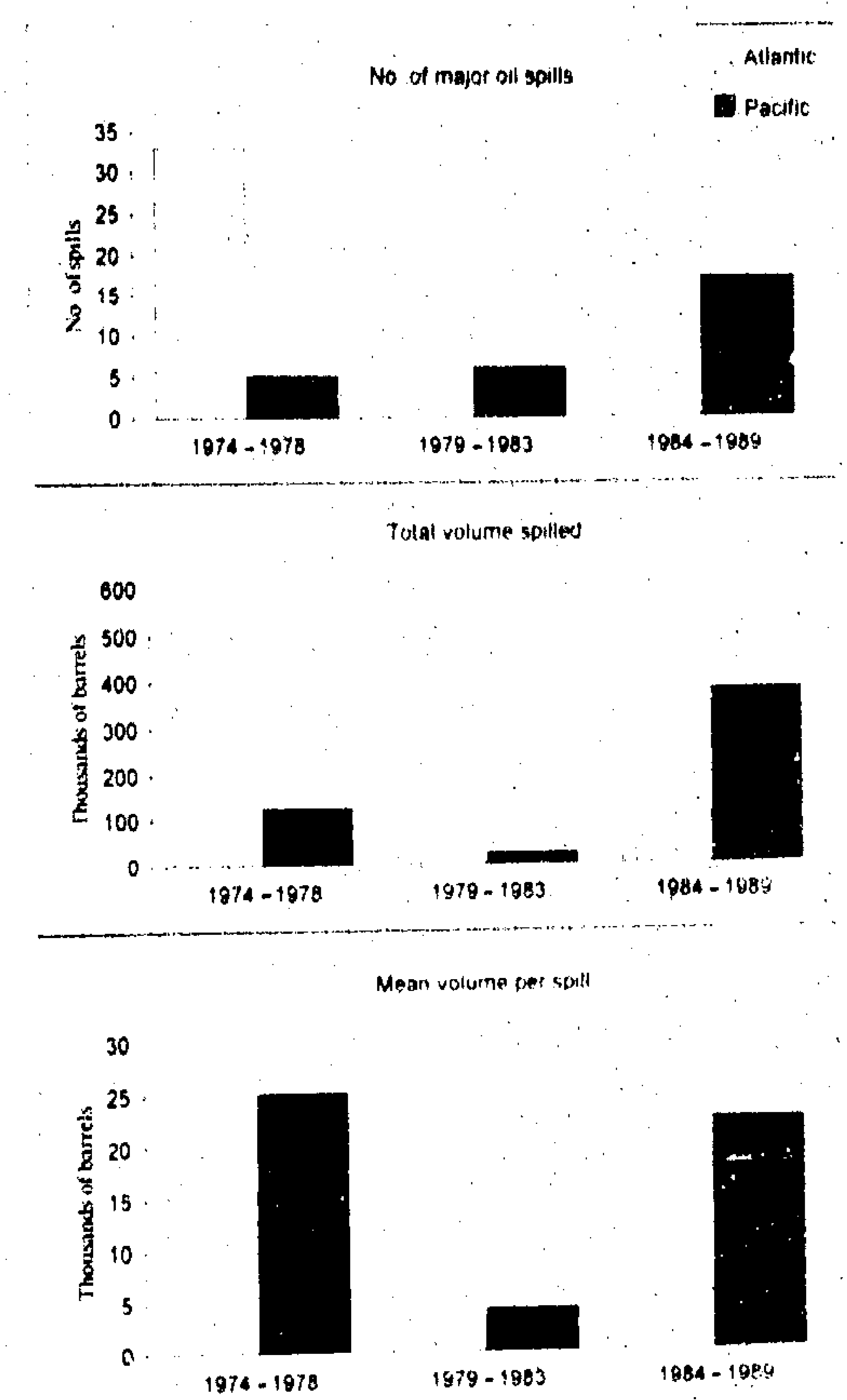
Burger (unpubl. data) found a weak correlation between the volume of oil spilled and the numbers of oiled birds, but concluded that this relationship could not be used in any predictive way and the statistical significance disappeared if the *Exxon Valdez* data were omitted. For most spill volumes one finds mortality estimates that range over more than two orders of magnitude (Fig. 2). Several well-documented spills from the North Pacific (*Apex Houston*, *Nestucca*, and *Exxon Valdez*) killed exceptionally large numbers of birds, reflecting the high densities of seabirds in the areas they affected.

3.2. Chronic low-volume spills

Seabird mortality caused by large spills from tankers or barges usually attracts public attention and official investigations, but the cumulative mortality of seabirds from small unreported spills may often be higher (Camphuysen 1989). Small volumes of oil may be released from leaking tanks and valves, accidents during loading or offloading, and flushing of tanks and bilges. In some areas, notably the North Sea (Vauk et al. 1989; Camphuysen and Franeker 1991) and off Newfoundland (Piatt et al. 1985), this low volume, chronic oiling is a major cause of seabird mortality.

In British Columbia 574 marine spills were reported in 1988, of which 22 (4%) exceeded 1 t (Kay 1989a, 1989b). The origin of almost half of these spills was not determined, and there were hundreds of small spills that were never reported.

Figure 1
The numbers of spills and volume of oil spilled reported from territorial waters of the United States in the Atlantic (including Puerto Rico, and excluding the Gulf of Mexico) and Pacific (including Alaska, Hawaii, and Pacific islands). The data from Cohen and Aylesworth (1990) are plotted in five-year intervals.



4. Methods for determining mortality from oil pollution

4.1. Beached bird surveys

Systematic monthly surveys of beaches have been used in many parts of the world to monitor the mortality and frequency of oiling of seabirds. Chronic oiling appears to be a significant cause of mortality in California; on the outer shores

Table 1
Mortality of seabirds resulting from oil spills in the North Pacific

Year (month)	Vessel name or source of the oil	Site	Spill volume (t)	Oiled birds: No. found	Oiled birds: Estimated mortality	References*
1991 (Jul.)	*Tenyo Maru* fish packer	Off Vancouver I., British Columbia	330 bunker and diesel	4 300	?	6
1989 (Apr.)	*Exxon Valdez* tanker	Pr. William Sound, Alaska	36 400 crude	31 000	350 000–390 000	4, 5, 7
1988 (Dec.)	*Nestucca* barge	Grays Harbor, Washington	770 bunker	12 535	56 000	10
1988 (Jan.)	Barge MCN5	Anacortes, Washington	240 gasoil	None reported		3
1987 (Oct.)	*Stuyvesant* tanker	150–300 km off northern B.C.	2 000 crude	Not known		3, 6
1986 (Feb.)	*Apex Houston* barge	San Francisco, California	87 crude	4 198	10 577	11
1985 (Dec.)	*Arco Anchorage* tanker	Port Angeles, Washington	800 crude	1 917	4 000	6, 12
1984 (Oct.)	*Puerto Rican* tanker	San Francisco Bay, California	4 900 mixed oils	1 300	4 815	8, 9
1984 (Dec.)	Unknown	Puget Sound, Washington	17 bunker	>406	>1 500	6, 13
1984 (Mar.)	*Mobiloil* tanker	Columbia River, Oregon	660 mixed oils	450	?	6, 13
1971 (Jan.)	collision	San Francisco, California	2 700 bunker	7 380	20 000	1, 2
1956	*Seagate* freighter	Olympic Peninsula, Washington	Not known		>3 000	2
1937	*Frank Buck* tanker	San Francisco, California	11 800 crude		10 000	2

* References:
1. National Research Council (1985)
2. Vermeer and Vermeer (1975)
3. Cohen and Aylesworth (1990)
4. Piatt and Lensink (1989)
5. Piatt et al. (1990)
6. Washington Dep. of Ecology (unpubl. data)
7. Stewart et al. (1991)
8. Point Reyes Bird Observatory (1985)
9. Ford et al. (1987)
10. Ford et al. (1991)
11. Page et al. (1990)
12. Speich (1986)
13. Speich and Thompson (1987)

Conversion: 50 barrels=7 tonnes (National Research Council 1985)
1 barrel=0.14 tonnes
1 tonne=approx. 1 ton
1 tonne=approx. 300 gallons (U.S.)
1 tonne=approx. 1 100 litres

of Washington, and in British Columbia, although the frequency of oiling appears to be lower than in some other parts of the world, such as Newfoundland, the Netherlands, and Belgium (Table 2). Direct comparisons between areas are difficult, because different criteria are used to assess the percentage of birds oiled. The cause of death cannot be determined for most beached carcasses. Oiled birds were found in all months, and in most cases had been affected by small amounts of heavy fuel or crude oil (Stenzel et al. 1988; Burger 1992). Birds may be killed by oil without external signs of oiling; Vauk et al. (1989) found that 20% of the beached carcasses that showed no external oiling contained oil.

4.2. Assessing impacts of major spills

The impact of a spill is usually gauged by the number of oiled birds found on beaches. These birds represent only a proportion of the affected population, and extrapolations need to be made to assess the overall impact on seabirds. Experiments and models have been developed in recent years to improve these assessments in the North Pacific. Models developed by Ford and associates have been applied to several spills in the North Pacific, including the *Apex Houston* and *Puerto Rican* spills in California (Ford et al. 1987; Page et al. 1990), the *Nestucca* spill off Washington and British Columbia (Burger 1990; Ford et al. 1991), and the *Exxon Valdez* spill (G. Ford, pers. commun.). In the latter two events the models provided key information used during litigation.

Beginning with the numbers of oiled birds recovered on beaches, Ford's model retroactively estimates the numbers of birds lost on the beaches and at sea. Critical input parameters include the day-to-day persistence of carcasses on the beaches, the rate at which carcasses sink at sea, the path of the drifting oil, and the distribution and densities of the birds in the path of the slicks. Factors that affect these models and other assessments are reviewed below.

Figure 2
Log–log plots comparing the numbers of seabirds oiled with the volume of oil spilled. The upper graph (A) shows the minimum bird counts, and the lower (B) the overall mortality estimated by each author (from Burger, in press). Some well-known spills in the North Pacific are labelled: AA, *Arco Anchorage*; AH, *Apex Houston*; EV, *Exxon Valdez*; NA, *Nestucca*; PR, *Puerto Rican*; TM, *Tenyo Maru*. See Table 1 for details on these events.

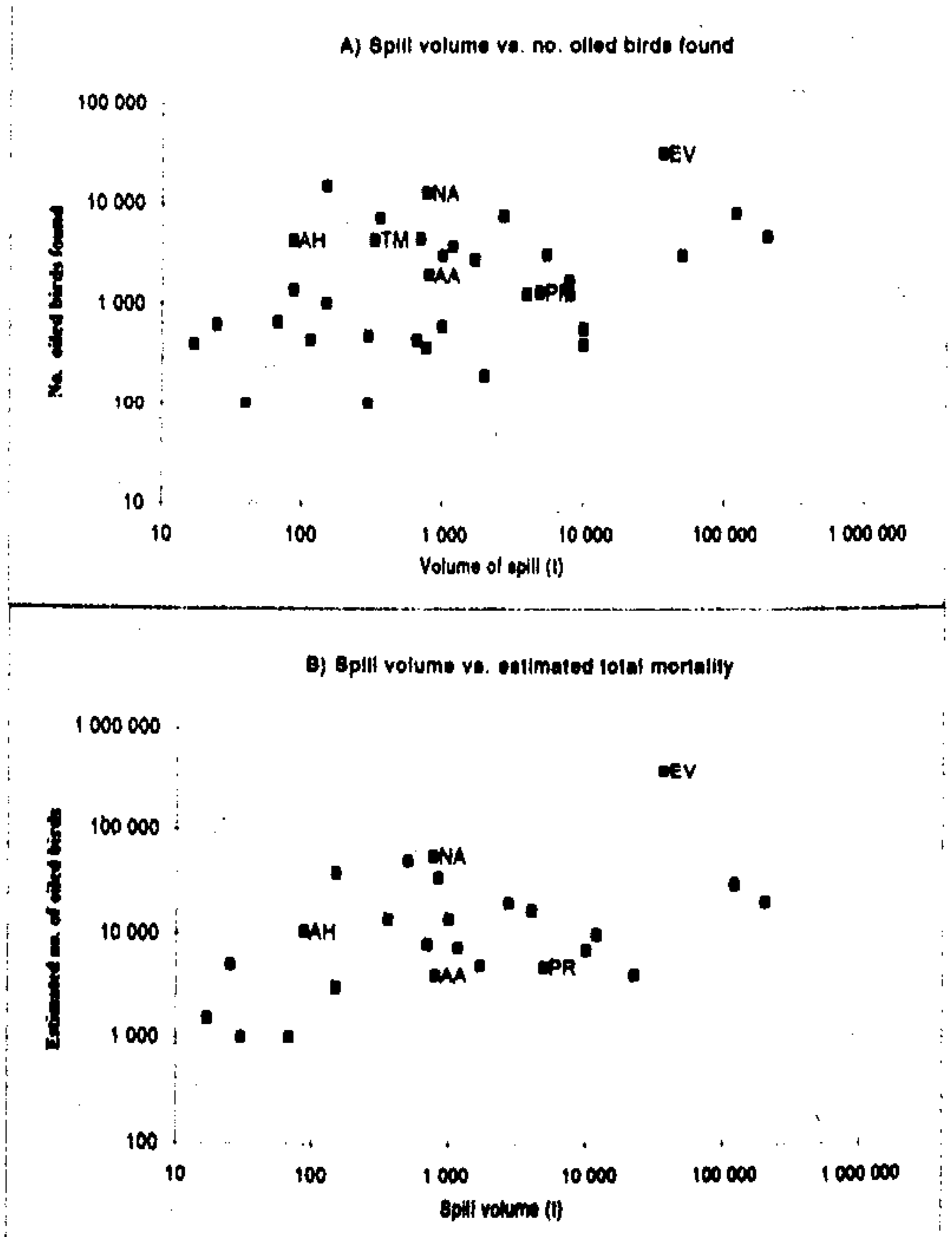


Table 2
Summary of beached bird surveys around the world

Country or region	Years of coverage [No.]	Mean distance per year (km)	Mean corpses per km	Proportion oiled corpses (%)	Approx. oiled corpses per km	References
British Columbia	1987–1992 [5]	180	0.40	8	0.04	Burger 1992
California	1971–1985 [14]	(91 beaches)	2.72	83% of known causes	–	Stenzel et al. 1988
Washington (inland marine)	1978–1979 [2]	48	0.26	<1	<0.01	Speich and Wahl 1986
Washington (open shores)	1981–1984 [4]	Not known	6.64	4.5	0.30	Speich and Wahl 1986
Atlantic U.S.	1975–1983 [8]	202	1.17	6.6 overall	0.08	Simons 1985
Newfoundland	1980–1987 [8]	68	7.1	23–65	1.63–4.62	Piatt et al. 1985, Elliott and Ryan 1988
Britain	1966–1983 [17]	?	?		0.27	Stowe 1982, Stowe and Underwood 1984
Shetland, U.K.	1979–1990 [10]	618	4.24	9.1	0.39	Heubeck 1987, in litt.
Netherlands	1969–1990 [21]	1282	4.5	68.4	3.08	Camphuysen 1989, in litt.
Belgium	1962–1977 [15]	63	3.7	70	2.59	Kuyken 1978
Portugal	1982–1990 [9]	1359	2.4	7.8	0.19	Teixeira 1986, in litt.

4.3. Effects of ocean currents and wind

Measurements of wind and current vectors, aerial surveys of bird distribution, and detailed tracking of the paths of slicks at the time of the spill are essential for accurate modelling of encounters between oil and flocks of birds (Ford et al. 1987; Page et al. 1990). Oiled carcasses drift under the influence of wind, currents, and tides. Wind direction and velocity appear to have the strongest influence in open water, and drifting carcasses tend to move at speeds of 2–3% of the wind velocity (Hope Jones et al. 1970; Bibby and Lloyd 1977; Ford et al. 1991). Wave action near the shore might act as a barrier to prevent carcasses from beaching, and most carcasses appear on the beaches following strong onshore winds (Camphuysen 1989).

In the waters off British Columbia and Washington, the prevailing winds blow from the NW in summer and SE in winter (Thomson et al. 1989). Combined with clockwise Coriolis forces the resultant surface vectors go offshore in summer and onshore in winter, suggesting that fewer carcasses are likely to come ashore in summer than in winter. The coastal currents that run parallel to the shore from California through British Columbia can carry oil and seabird carcasses hundreds of kilometres, but might also act as barriers to cross-shelf movements (Thomson et al. 1989) and hence lower the probability that oiled carcasses will come ashore.

4.4. Persistence of oiled carcasses at sea

Oiled carcasses may sink, be scavenged by fish or birds before they come ashore, or be washed back to sea from beaches. The rate at which carcasses lose their buoyancy and sink depends on the type of bird, and the exposure to wind and waves. Diving birds (loons, grebes, cormorants, and alcids) have higher density than more aerial species (shearwaters, petrels, gulls, phalaropes) and are more likely to sink at sea, thus skewing the estimated species composition of spill victims.

Reports from Britain estimate that 11–58% of birds killed at sea sink before coming ashore (Coulson et al. 1968; Hope Jones et al. 1970; Bibby and Lloyd 1977). Ford et al. (1991) found that murre carcasses tethered in sheltered and exposed seas in Oregon remained afloat for an average of 8.4 and 7.6 days respectively. They tracked radio-tagged murre carcasses freely drifting off Washington. The rate of sinking fitted a predictable survivorship curve with more than 90% disappearing within 14 days at sea.

Burger (1991a) tested heavily oiled carcasses in a tank simulating benign ocean conditions. Carcasses of Ancient Murrelets *Synthliboramphus antiquus* and Common Murres *Uria aalge* behaved similarly (2% of the original sample sank per day), whereas Horned Grebes *Podiceps auritus* sank more quickly (9% per day). When floating carcasses were ripped open to simulate scavenging, nearly all of them immediately sank.

4.5. Persistence of carcasses on the shore

Many oiled carcasses which come ashore may be covered by sand or jetsam, washed back to sea, or removed by scavengers before they can be tallied. Scavenging birds and mammals are common on Pacific shores and eat or remove oiled carcasses (Burger 1990, 1991b; Wood and Heaphy 1991). Measures of the day-to-day persistence of carcasses on beaches in the eastern North Pacific range from 0.38 through 0.84 (Table 3). This measure is a highly sensitive variable in models that estimate the total number of carcasses coming ashore after a spill (Ford et al. 1987, 1991; Page et al. 1990; Burger 1990) and, ideally, should be determined at the time of the spill.

Scavenging of carcasses is also a major source of secondary oiling. Oiled gulls, eagles, falcons, and other birds have been reported following major spills (Lowell 1986; Burger 1991b; Wood and Heaphy 1991). The impacts of this secondary oiling may be underestimated, because the scavengers often roost away from the beaches and may die undetected. About 90% of the radio-tagged Bald Eagles *Haliaeetus leucocephalus* that died in studies which followed the *Exxon Valdez* spill were found in brush, away from the beachfront (Stewart et al. 1991).

4.6. Experiments with drifting carcasses and blocks

Experimental releases of bird carcasses, or bird-sized wooden blocks, have been undertaken to estimate the proportions of oiled populations likely to be found ashore. Hope Jones et al. (1970) found 20% of the oiled alcids released off well-searched beaches in England, while Bibby and Lloyd (1977) recovered 11%, 44%, and 59% of the gulls released upwind of beaches in three separate trials. In a series of experiments, carcasses of gulls, murres, and auklets were dropped 500–1000 m off Bolinas Beach, California (Point Reyes Bird Observatory 1985). Two-thirds of the 43 gull carcasses were found on the beach, but none of the 54 murres or nine auklets, indicating that mortality estimates of the alcids are likely to be underestimated. Only three out of 100 oiled murres killed by the *Exxon Valdez* spill that were tagged and re-released at sea were subsequently recovered (Piatt et al. 1990).

Bird-sized wooden blocks were used by Hlady and Burger (1990) off Vancouver Island. After one month, 53% of 600 blocks released 1 km offshore were recovered in winter, and 43% in a similar release in summer. Only 10% of 300 blocks released 35–116 km offshore in winter were recovered,

Table 3
Persistence of bird carcasses on beaches on the Pacific coast, shown as the mean proportion of samples of carcasses remaining on the beach from one day to the next

Site	Birds used	Persistence	Reference
California	Oiled alcids	0.59	Page et al. 1990
Washington	Common Murres	0.74	Ford et al. 1991
Vancouver Island	Intact chickens	0.84	Humphries 1989
Vancouver Island	Chicken portions	0.38	Dale 1989
Vancouver Island	Shearwaters and kingfishers	0.45	Burger 1991a
Alaska	Oiled alcids	0.80–0.84	Piatt et al. 1990

Blocks were found to travel hundreds of kilometres, but most were found within 10 km and 16 days of release. This result probably overestimated the proportions of carcasses likely to be recovered, because the blocks were more conspicuous (painted red) and more buoyant than carcasses, and were not subjected to scavenging.

These results indicate that a large proportion of oiled seabirds would never be recovered, despite intensive searches on the beaches. A few oiled carcasses found on a beach might be the only indications of a major kill resulting from an unreported spill far offshore.

5. Effects of oil on birds

There have been numerous studies of the effects of oil on birds (see reviews by National Research Council 1985; Fry and Lowenstine 1985; Leighton et al. 1985; Leighton 1991). Some important findings are reviewed here.

5.1. Effects of oil on plumage, buoyancy, and thermoregulation

Fouled plumage is acknowledged to be the primary cause of mortality and stress in oiled birds (National Research Council 1985; Leighton 1991). Oiled feathers lose their ability to keep body heat in and cold water out. Reduced insulation, increased metabolic rate, and hypothermia are well documented in oiled birds, and these effects may be produced by as little as 12.5 mL of heavy oil on the plumage (Hartung 1967; McEwan and Koelink 1973). Waterlogging and loss of buoyancy in oiled birds (McEwan and Koelink 1973; National Research Council 1985) further compound the injury and can rapidly lead to drowning.

5.2. Toxic effects of ingested oil

Secondary effects of ingestion of oil have been studied in a number of bird species, but general conclusions are difficult to reach, because of the variability in the chemical composition of the oils and the species and age of birds tested (Leighton 1991). There is no doubt, however, that most petroleum oils, including bunker and crudes, contain compounds that are highly toxic to birds and cause damage and sometimes death when ingested (National Research Council 1985; Fry and Lowenstine 1985; Leighton et al. 1985; Leighton 1991).

Most studies have investigated the effects of bunker fuel and crude oils. Although the composition of these oils differs, many of the toxic effects are similar (National Research Council 1985; Fry and Lowenstine 1985). Most contain high proportions of polynuclear aromatic hydrocarbons (National Research Council 1985), which are known to damage avian tissues (Miller et al. 1982; Peakall et al. 1983; Fry and Lowenstine 1985; Leighton et al. 1985). Weathering of oil at sea leads to the loss of volatile and water-soluble components, with subsequent enrichment of long-chain aliphatics, polynuclear aromatics, and asphaltenes, which increases toxicity (National Research Council 1985; Fry and Lowenstine 1985). Scavengers that ingest weathered heavy oil would be exposed to toxins.

5.3. Effects of oil on the alimentary tract

Both crude and bunker oils produced intestinal irritation in birds, which in some cases led to bleeding (Hartung and Hunt 1966; Langenberg and Dein 1983; Fry and Lowenstine 1985), although lesions were not reported from all experimental studies (Leighton 1991). Water and electrolyte transport across the intestinal membranes may be affected by oil (Crocker et al. 1974, 1975). The uptake of glucose and amino acids was depressed in Herring Gull *Larus argentatus* nestlings given South Louisiana crude containing high levels of polyaromatic hydrocarbons, but uptake was unaffected by aliphatic oils (Peakall and Hallett 1982; Peakall et al. 1983). A very small volume (0.2–0.5 mL) of crude oil fed to Herring Gull and Black Guillemot *Cepphus grylle* chicks caused accumulation of oil particles within intestinal tissues, which appeared to affect nutrient uptake, because the growth of the chicks was significantly retarded (Miller et al. 1978; Peakall et al. 1980). Reduced chick growth after oil ingestion has also been reported in storm-petrels (Trivelpiece et al. 1984; Boersma et al. 1988).

5.4. Effects of oil on blood

Oils with high polyaromatic hydrocarbon contents (such as Bunker C) are known to cause precipitation of hemoglobin leading to anemia (Leighton et al. 1983). Anemia in oil-dosed birds has been reported from many studies, and can result from small doses given over short periods (reviewed by Leighton et al. 1985; Fry and Lowenstine 1985; Leighton 1991). Up to 80% of circulating blood cells may be destroyed (Fry and Addiego 1987).

5.5. Effects on salt glands and osmoregulation

The osmotic regulation of blood and tissue fluids is influenced by several organs, including intestines, kidneys, and salt glands, which might be susceptible to oil toxicity. Elevated Na^+ levels in the blood and reduced $Na^+ K^+$-ATPase enzyme levels in the nasal salt glands have been reported in gulls and guillemots fed 0.2 mL of crude oil (Miller et al. 1978; Peakall et al. 1980, 1983). These studies reported enlargement of the nasal glands in the affected birds. Bunker oil applied externally to Glaucous-winged Gulls *Larus glaucescens* produced significant changes in plasma ionic concentrations and water flux (Hughes et al. 1990). In addition to direct toxic effects of oil on salt glands, osmoregulation may be affected by adrenal toxicity and stress effects leading to impaired synthesis, release, or regulation of corticosterone secretion. Osmotic stress can be fatal, or can exacerbate the effects of shock and cold stress in oiled birds (Holmes et al. 1978, 1979).

5.6. Effects of oil on adrenal glands and corticosteroid hormones

Significant changes in the size of adrenal glands and levels of corticosteroid hormones have been found in several studies where small amounts of oil were fed to birds, including gulls (Rattner et al. 1984; Fry and Lowenstine 1985; Leighton 1991). It is not clear whether all responses were directly caused by toxicity of oil or were stress responses to noxious stimulation. Oil is known to have direct effects on the adrenal glands, plus feedback regulatory effects on ovarian and salt gland function (Gorsline and Holmes 1981, 1982; Gorsline 1982). Large decreases in circulating corticosterone are probably due to both decreased adrenal secretion as well as increased liver metabolism of circulating steroids. Ingested oil given to ducks under temperature or osmotic stress causes increased mortality (Holmes et al. 1978, 1979). The combined effects of osmotic and adrenal stress caused by internal assimilation of oil and thermal stress due to oiled plumage are thus likely to be additive and lead to mortality.

5.7. Effects on kidneys and liver

Liver and kidney damage were reported as direct effects of crude and fuel oil ingestion in several studies on birds (Fry and Lowenstine 1985). Necrosis of kidney tubules was found in several oiled seabirds, including three out of seven Common Murres oiled by Bunker C fuel (Fry and Lowenstine 1985). Renal tubular necrosis could lead to water balance and electrolyte stress, as well as impaired excretion of metabolic wastes.

The liver plays a major role in metabolism and detoxification and is affected by oil. The ingestion of oil induces the activity of mixed-function oxidases (MFOs) responsible for metabolizing hydrocarbons. Increased MFO activity may also increase the turnover of corticosteroids and other steroid hormones, leading to decreased levels in the blood of oiled birds (Gorsline and Holmes 1981; Rattner et al. 1984). Degeneration of liver cells and fatty infiltration of the liver were found in ducks exposed to fuel oils, including Bunker C (Hartung and Hunt 1966; Langenberg and Dein 1983), but was not evident in acutely exposed murres oiled by Bunker C (Fry and Lowenstine 1985). Disassociation of liver cells observed with acute exposure indicates functional impairment, and may be a precursor of degeneration and fatty infiltration. Increased iron and heme metabolites in liver cells were found in most of the oiled auks examined by Fry and Lowenstine (1985), correlated with Heinz body hemolytic anemia.

The effects of oil in the liver are complex, representing both normal responses to foreign chemicals, as well as toxic responses resulting in impaired liver function. Heavily oiled birds in rehabilitation centres frequently die with clinical symptoms indicative of liver failure.

5.8. Effects on reproductive performance

Ingested oil causes short- and long-term reproductive failure in birds, indicative of severe physiological problems. These include delayed maturation of ovaries, altered hormone levels, thinning of eggshells, reduced egg productivity, reduced survival of embryos and chicks, reduced chick growth, and abandonment of nests by adults (Grau et al. 1977; Miller et al. 1978; Wootton et al. 1979; Peakall et al. 1980; Ainley et al. 1981; Trivelpiece et al. 1984; Fry and Lowenstine 1985; Fry 1987; Boersma et al. 1988). Significant effects were usually dose dependent, but were often produced by very small amounts of ingested oil. For example, a dose of 200 mg of Bunker C oil caused shell thinning, reduced egg production, and higher embryo mortality in quail (Grau et al. 1977; Wootton et al. 1979), whereas single doses of 0.3 mL led to reduced hatching and fledging success and reduced growth and survival of chicks in storm-petrels (Trivelpiece et al. 1984; Boersma et al. 1988; Butler et al. 1988).

5.9. Suppressed immunity

Ingestion of oils can reduce the functions of the immune system and reduce resistance to infectious diseases (Leighton 1991). Decreased levels of blood lymphocytes in Herring Gulls, decreased numbers of immune cells in lymphoid organs in Mallards *Anas platyrhynchos* and Herring Gulls, and decreased resistance to bacterial disease in Mallards have been demonstrated following experimental oil ingestion (Leighton 1991).

5.10. Mutagenic effects

Mutagenic effects of polynuclear aromatic hydrocarbons have been demonstrated (Payne and Martins 1978; Guerin et al. 1980, 1981; Sheppard et al. 1983; National Research Council 1985; Fry and Lowenstine 1985). Long-term mutagenic effects are difficult to monitor in birds, but such changes could have significant effects in long-lived species such as seabirds (Fry and Lowenstine 1985).

5.11. Conclusions on the effects of ingested oil

Most mortality of oiled birds results from the fouling of their plumage, retarded thermoregulation, and the associated stress. It is clear, however, that ingestion of even small amounts of oil usually leads to multiple physiological changes, which could impair a bird's ability to survive at sea (Miller et al. 1978). The synergistic effects of oiled plumage, osmotic and thermal stress, and anemia could greatly increase the mortality of birds under adverse environmental conditions (Leighton 1991).

6. Long-term effects of oiling in seabirds

6.1. Long-term effects on individual birds

The effects of sublethal experimental doses of oil have seldom been tracked over more than one season. Small doses of oil fed to breeding Leach's Storm Petrels *Oceanodroma leucorhoa* caused significantly reduced reproduction, but the effects were not detected in the following season (Butler et al. 1988). By contrast, Fry et al. (1986) found that 2 mL of crude oil applied to the feathers of Wedge-tailed Shearwaters *Puffinus pacificus* caused complete reproductive failure in the season of treatment, largely due to nest abandonment and reduced hatching success, and the reproductive success was also reduced in the following season. The residual effects in the second season were not directly attributed to ingestion of the externally applied oil, but were correlated with the disruption of pair-bonds after breeding failure.

6.2. Effects of oil spills on populations

No species of North Pacific seabird has been threatened with extinction as a direct result of oil spills, but local populations have been substantially reduced as a result of spills. These changes are difficult to detect, for many reasons, including: the difficulties of censusing burrowing and cliff nesting seabirds; the absence of a prior series of complete colony censuses in most parts of the North Pacific; and the problems of separating the spill effects from year-to-year variations in population and attendance due to natural phenomena (e.g., El Niño effects).

The cumulative effects of the *Puerto Rican* and *Apex Houston* spills, gillnet mortality, and a severe El Niño event are linked to a decline of 53%, within 4–6 years, at colonies of Common Murres in central California (Takekawa et al. 1990). The *Tanyo Maru* spill off Washington killed thousands of murres and their fledglings, from a population already severely reduced as a result of El Niño events (Wilson 1991).

The *Exxon Valdez* spill was estimated to kill about 10% of the population of Common Murres in the Gulf of Alaska and >50% of the population breeding at the Barren Islands (Piatt et al. 1990). Colony surveys indicated that 120 000–140 000 breeding adult murres were killed, and some colonies lost 60–70% of the breeding adults (Stewart et al. 1991). Changes in the spatial structure of the impacted colonies and in bird behaviour caused almost complete breeding failure in 1989 and 1990 and the lost production of at least 215 000 murre chicks (Stewart et al. 1991). Local populations of Marbled Murrelets *Brachyramphus marmoratus* and Pigeon Guillemots *Cepphus columba* were also decimated, but the overall gulf populations might not have been severely affected (Piatt et al. 1990). Bald Eagles in Prince William Sound had reduced breeding success in the oiled areas in 1989 (Stewart et al. 1991), but this did not persist in subsequent years, and there was no indication of significant population decline (Gibson 1991).

Surveys at the major colonies of Common Murres and Cassin's Auklets *Ptychoramphus aleuticus* in British Columbia produced no evidence of a decline in the summer following the *Nestucca* spill (Rodway 1990; Rodway et al. 1990), but the census techniques and comparative data might not have been sensitive enough to detect significant changes, and many of the dead birds might have come from other colonies.

7. Rehabilitation of oiled seabirds

7.1. Short-term success of rehabilitation programs

Early attempts to rehabilitate oiled seabirds had little success. For example, over 95% of the birds treated after the 1971 San Francisco spill died in captivity (Smith 1975). Rehabilitation techniques have improved considerably since then. One-third (1027) of the 3092 oiled birds found alive on beaches in Washington, following the *Nestucca* spill, were returned to sea after cleaning (Ford et al. 1991). Following the *Exxon Valdez* spill, 50.7% of the 1630 oiled birds received at cleaning stations were released back to the wild (Wood and Heaphy 1991).

7.2. Long-term survival and success of rehabilitated birds

Large amounts of money are spent in rehabilitation programs, but there appear to be few attempts to assess their long-term effectiveness. The post-release survival of rehabilitated seabirds is relevant to analysis of the impacts of spills. Such data not only provide estimates of the portion of cleaned birds that recovers fully, but also give some indication of the survival chances of those oiled birds that avoid capture and clean the oil off their plumage by themselves.

There are several problems associated with determining the post-release survival of rehabilitated birds. Free-living seabirds are extremely difficult to monitor after their release. It is often impossible to determine the colony from which oiled birds originated, and such colonies are often in a different jurisdiction to the site of the spill. Detailed, long-term censuses at colonies, which might detect population changes or monitor the return of banded rehabilitated birds, are expensive and logistically difficult to maintain. Many oiled victims are immatures and their survival cannot be checked at breeding colonies.

Despite the difficulties, it is surprising that wildlife agencies and rehabilitation organizations have made few attempts to monitor rehabilitated birds, even though this was identified as a research priority long ago (Bourne 1968a). Radio-telemetry, analysis of band-returns, or comprehensive beached bird surveys could all be applied.

Radio-telemetry was used in a study comparing rehabilitated Brown Pelicans *Pelecanus occidentalis* (victims of the *American Trader* spill) with unoiled wild-caught conspecifics in California (Anderson et al. 1991). The rehabilitated pelicans remained near the site of release, made shorter foraging trips, and were less mobile than the controls for six months after their release. Only one out of 21 rehabilitated birds visited a breeding colony, compared to the 37% of controls that made multiple trips to colonies. The rehabilitated birds also delayed their northward migration in summer, relative to controls.

Following the *Arco Anchorage* spill off Port Angeles, Washington, in 1985, 281 cleaned birds were released and nearly all were banded. Of these, seven were recovered during intensive beach surveys in the subsequent six weeks, yielding a minimum recovery rate of 2.5% (Speich 1986). Speich concluded that many other birds died in the release area and sank or went undetected on beaches, and some birds undoubtedly left the release area. This rate of mortality is much higher than that expected of seabirds, which tend to have an annual mortality of about 10%.

Rehabilitated birds kept in captivity following the normal time of release have been found to suffer a range of physiological disorders (Kahn and Ryan 1991), and have lower survival than unoiled controls (Swennen 1977). Relatively high survival rates have been found among rehabilitated penguins (Randall et al. 1980; Morant et al. 1981), but some biologists question the efficacy of cleaning programs even for these robust birds (Frost et al. 1976). Seabird biologists in Europe, where oiling has long been a major concern, appear to be in agreement that rehabilitation programs serve no valuable purpose in maintaining seabird populations, although they might serve humanitarian purposes (Bourne 1968a, 1970; Swennen 1977; Clark 1984; Vauk 1984; Peeters 1991). Clearly this is an issue that should be addressed through intensive field research.

8. Conclusions and future research priorities

Seabirds will continue to be oiled in the North Pacific from oil spilled in catastrophic tanker and barge accidents or from the thousands of small spills in marinas and ports. Techniques for assessing the impacts of these spills have improved greatly over the past decade, but many estimates of mortality depend largely or entirely on educated guesses rather than hard facts. Recent spills have been followed by litigation involving millions of dollars in compensation for damage to wildlife. Judges and lawyers are demanding information that seabird biologists cannot readily provide. More importantly, the biological impacts of major and minor spills on local seabird populations are still poorly understood.

We suggest the following priorities for research, not necessarily in order of importance.

(1) More information is needed on the fate of oiled birds at sea and on the shore to improve the accuracy of assessment models. Changes in buoyancy of carcasses, persistence of carcasses at sea and ashore, and responses of carcasses to wind and currents can often be measured using simple, inexpensive procedures.

(2) Ornithologists need to go to sea after spills to observe how birds respond to oil in the water. There is remarkably little information on this topic (Bourne

1968b). Perhaps we can develop deterrents to protect birds?

(3) We need to know the long-term effects of exposure to oil. Very few studies on the effects of oil on physiology and breeding biology extend beyond two or three years. Seabirds may live for many decades and so we need to know whether exposure to oil has significant effects over many years.

(4) The long-term efficacy of cleaning and rehabilitation programs should be assessed. Are the time and money spent on rehabilitation justified, relative to its effect on individuals and populations? Behavioural studies using radio-telemetry might tell us when and how to release birds to maximize their long-term survival.

(5) Research into the effects of spills needs to be ongoing, and not initiated purely as a reaction to a major spill. Reducing the impact of a major spill, or estimating the resultant mortality, can be achieved more readily if there is a good understanding of the seasonal and spatial distribution of birds, their responses to local oceanic conditions, and the likely hot-spots where seabirds might be especially vulnerable.

(6) We need the ability to determine the origins of birds affected by spills. Morphometric, biochemical, and genetic parameters should be investigated as indicators of local genotypes. This has happened to a far greater degree in the North Atlantic than in the Pacific. This knowledge would allow us to look in the most likely places to detect impacts of oil spills, and to identify the characteristics of particularly sensitive populations.

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