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TROUBLE ON OILED WATERS: Lessons from the *Exxon Valdez* Oil Spill

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ABSTRACT

The *Exxon Valdez* oil spill was the largest in US maritime history. We review post-spill research and set it in its legal context. The Exxon Corporation, obviously responsible for the spill, focused on restoration, whereas the Trustees, a coalition of state and federal entities, focused on damage and its assessment. Despite billions of dollars expended, little new understanding was gained about the recovery dynamics of a high latitude marine ecosystem subject to an anthropogenic pulse perturbation. We discuss a variety of case studies that highlight the limitations to and shortcomings of the research effort. Given that more spills are inevitable, we recommend that future studies address spatial patterns in the intertidal, and focus on the abundances of long-lived species and on organisms that preserve a chronological record of growth. Oil spills, while tragic, represent opportunities to gain insight into the dynamics of marine ecosystems and should not be wasted.

> "You get a guy with four PhDs saying no fish were hurt, then you get a guy with four PhDs saying, yeah, a lot of fish were hurt. . . . They just kind of delete each other out." (Barker 1994, p. 74)

INTRODUCTION

The *Exxon Valdez* oil spill (EVOS) is likely to be remembered as one of the great environmental tragedies of North America in the late twentieth century. Through pictures of dead birds, struggling baby seals, and great dark stains across pristine beaches framed by snowcapped mountains, the spill imposed

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itself upon the public consciousness. Collective outrage provoked costly cleanup new federal legislation, and the most expensive settlement for oil spill damages ever, though the case is still in litigation. This paper represents an analysis of some of the ecological research performed after EVOS. Enormous effort has gone into post-spill research, with many results yet unpublished or buried in gray literature. Clearly we cannot summarize all that has been done. Thus, we have focused our efforts on three areas:

1. to set the stage for the scientific response to EVOS, we detail the limitations on research imposed by US environmental legislation;
2. we discuss EVOS research that is particularly representative of the results, problems, or conflicts associated with the studies; and
3. we describe the sorts of research and monitoring that we believe might be more useful when future spills occur, as they surely will.[1]

We take the perspective that oil spills and subsequent cleanup activities are pulse perturbations to communities. Pulse perturbations, which are one-time, short-term alterations of some component of an ecosystem, are commonly used by ecologists (usually at smaller scales and by manipulating factors other than hydrocarbon concentration) to explore the dynamic interconnectedness of biotic systems. The few scientific conclusions that can be reached after six years of study and the expenditure of hundreds of millions of dollars suggest the inefficiency of the research effort and the squandering of a rare albeit unfortunate opportunity.

QUANTITIES AND COSTS

Grounding of the T/V Exxon Valdez

On 24 March 1989, shortly after midnight, the single-hulled bulk oil carrier T/V *Exxon Valdez* ran aground on Bligh Reef in the eastern part of Prince William Sound, Alaska (PWS 61°02′N, 146°05′W), spilling approximately 36,000 metric tons (10.8 million gallons) of North Slope crude oil onto a topographically varied, biologically rich, and poorly known, high latitude marine ecosystem (112). The spill, the largest to date in US maritime history, had a number of immediate repercussions: It shocked the American public, dominating the news

[1] As we write, efforts are underway to control the 15 February 1996 spill from the *Sea Empress*, a single hull supertanker carrying 132,000 metric tons (36.7 million gallons) of North Sea light crude oil. The tanker ran aground off the coast of Wales (UK), spilling to date at least 88,000 metric tons (20 million gallons).

media for weeks; individuals and organizations were galvanized into action, generating an economic boom for southeast Alaska; the Oil Pollution Act of 1990 was passed by Congress; the spill thwarted then-President Bush's intent to explore for and exploit known and suspected oil reserves in the Alaska National Wildlife Refuge; and it generated the largest corporate response and subsequent fine in US financial history.

EVOS Compared to Prior Spills

What is lost among these superlatives is the fact that the spill was hardly exceptional: Of spills occurring between 1967 and 1994 in excess of 1000 metric tons, EVOS ranked 40th (4, 116) (Figure 1). By comparison, over 6500 times more oil (240 million metric tons) was released from January to June 1991 in the Persian Gulf. On the other hand, EVOS shares numerous similarities with other large spills: It was caused by human error; its occurrence was inevitable, although the magnitude, timing, and position were not; and it affected a site characterized by scant pre-existing environmental data (64, 78, 157).

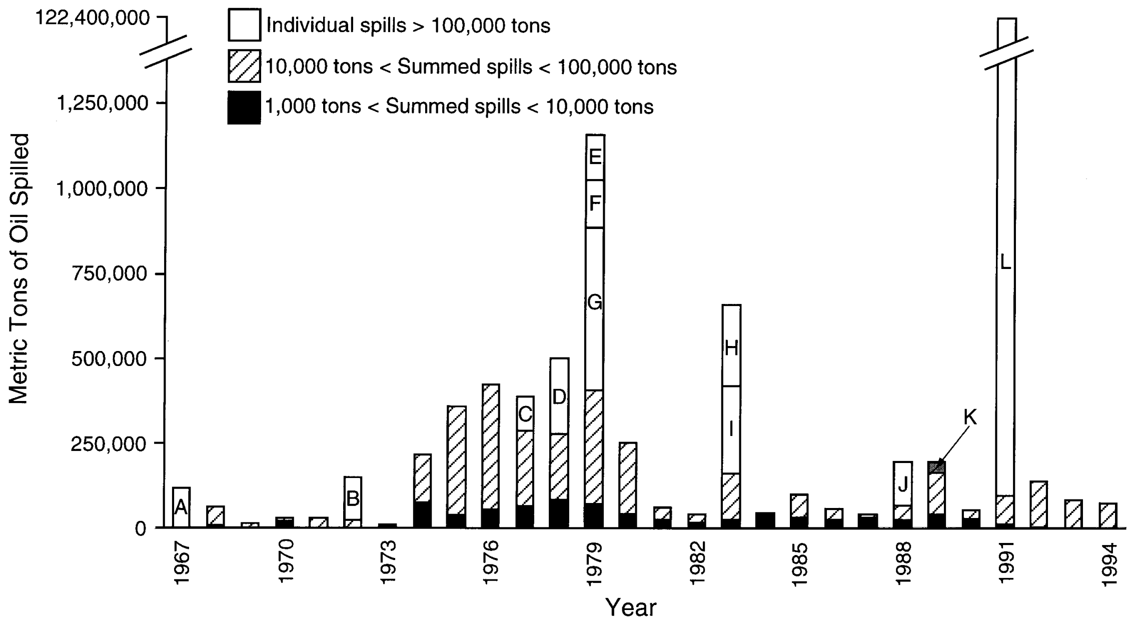
EVOS Oil Trajectory

After the grounding, oil was blown onto southwestern islands (Figure 2) by storm winds coming from the northeast three days after the spill. Within three weeks, about 40% of the spilled oil landed on Prince William Sound beaches, and one fourth of the oil moved into the Gulf of Alaska (56, 57). Oil traveled as far as 750 km from the spill site, contacting 1750 km of shoreline along the way (900 km in PWS) (76, 100). Some beached oil was collected by cleanup crews, but much eventually ended up back in the water column, lifted off beaches when they were washed by humans or pummeled by winter waves (67, 82, 107, 172).

Oil that was not collected during cleanup disappeared from the environment in two ways: through evaporation and through degradation into other carbon-based compounds. The lightest, most toxic fractions probably evaporated within the first 10 days and constituted no more than 20% of the total amount (172). Degradation of heavier oil fractions takes a great deal longer and is often assumed to follow an exponential decline, as hydrocarbons are broken down by light and by microbial consumers (172). Five years after the spill, about 2% of the oil remained on beaches and 13% in sediments, with only a tiny fraction still dispersed in water (172).

Cleanup Operations

Cleanup of oil following previous high-latitude coastal spills often met with limited success. Booms to cordon off stretches of shoreline become ineffective in stormy seas; boats equipped to skim oil off the water surface prove fruitless when entangled in macroalgae [e.g. Santa Barbara oil platform spill in 1969



A. Torrey Canyon (18 Mar 1967; 116,960 tons)
B. Sea Star (19 Dec 1972; 127,432 tons)
C. Hawaiian Patriot (23 Feb 1977; 100,912 tons)
D. Amoco Cadiz (16 Mar 1978; 221,408 tons)
E. Atlantic Empress (2 Aug 1979; 134,329 tons)
F. Atlantic Empress (19 Jul 1979; 138,279 tons)
G. IXTOC I (3 Jun 1979; 479,046 tons)
H. Nowruz Oil Field (10 Feb 1983; 259,048 tons)
I. Castillo De Bellver (6 Aug 1983; 239,360 tons)
J. Odyssey (10 Nov 1988; 129,594 tons)
K. Exxon Valdez (24 Mar 1989; 32,708 tons)
L. Arabian Gulf/Kuwait (19 Jan 1991; 122,400,000 tons)

Figure 1 Magnitudes of oil spilled into the ocean since 1967. From (4, 116) and *Oil and Gas Journal*, Vol. 91–92 (1993–1994)

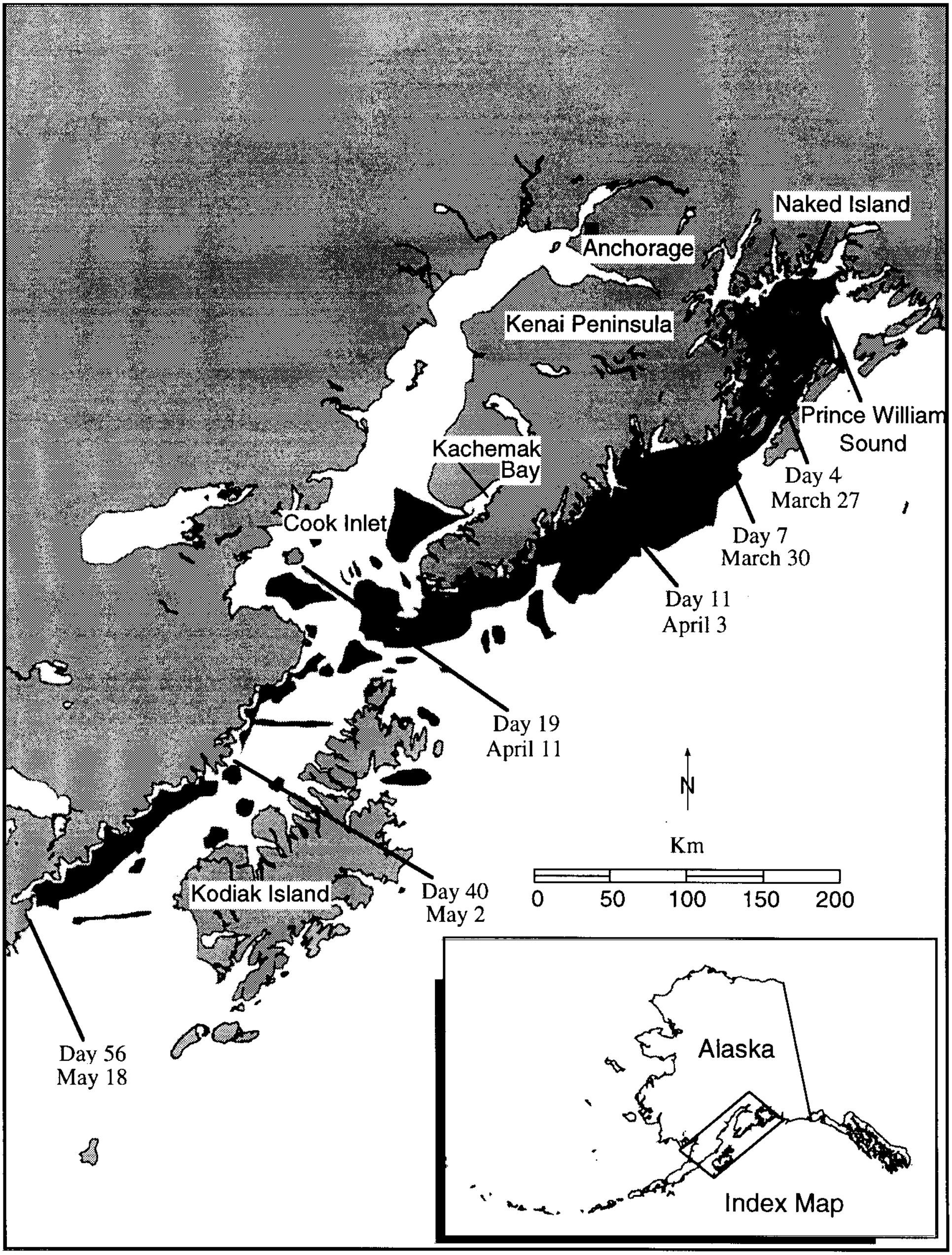


Figure 2 Spread of oil spilled from T/V *Exxon Valdez* during the initial 56 days. Courtesy USDA Forest Service (from 27).

(115, 149)]; dispersants, detergents, and hot water cleaning of shoreline cause substantially more mortality than oil itself, with extended effects on intertidal dynamics [e.g. *Torrey Canyon* tanker in 1967, *Amoco Cadiz* tanker in 1978 (12, 18, 62, 65, 70, 145)]. The acute toxicity of oil in terms of birds and mammals killed has become legendary. In contrast, on shorelines exposed to high wave energy, the developing wisdom is that the cleanup "cure" does more environmental damage than the spill (50, 59, 65, 118).

After EVOS, federal legislation and public outrage required a variety of immediate remediations. Booms were deployed selectively to keep oil from contaminating salmon hatcheries, while fishing in oiled areas was prohibited in 1989 (140). Oiled birds and mammals were retrieved and brought to rehabilitation centers (73, 109). Exxon used the world supply of booms and skimmers, involved 1500 boats in assessment, cleanup, and wildlife rescue, and organized some 12,000 people to remove oil manually from beaches (61, 100). Most of the moderately to heavily oiled shorelines in PWS (>500 km) were sprayed with seawater, often at high pressures and temperatures, and about 110 km of shoreline were treated with fertilizer in 1989 to stimulate natural biodegradation (6, 20, 76, 105, 137). These efforts removed 10–14% of the total oil spilled (61, 172), and required 40 times that much oil to run the boats and equipment involved in cleaning (61). A day after the grounding, a small portion (< 0.27%) (87, 172) of the spill was used to test the effectiveness of burning, and up to 98% of the trapped oil burned away (3). No further burning was carried out, either because too many of the volatile oil fractions evaporated and the oil would not ignite (87), or because smoke from the experimental burn distressed unprepared and unwarned Alaskans, and the Coast Guard forbade larger efforts (166). Some estimates suggest that 50% of the *Exxon Valdez* spill could have been burned without any danger to the ship itself (42).

Costs of EVOS

EVOS provided southeast Alaska with a short economic boom, as the media converged to cover the disaster and funds from Exxon for cleanup and compensation poured in. Exxon paid immediate post-spill costs to fishermen and cleanup workers ($2300 million) and eventually reached an out-of-court settlement with Federal and State officials to pay $900 million more over 10 years to "restore the resources injured by the spill, and the reduced or lost services (human uses) they provide" (155) (Table 1). The money, which supports research and restoration projects, is administered by the six-member EVOS Trustee Council.[2]

[2]Attorney General of Alaska; State Commissioner of Environmental Conservation; State Commissioner of Fish and Game; Assistant Secretary of Interior; Director of the Alaska Region of National Marine Fisheries Service; Alaska Regional Forester for Department of Agriculture.

Table 1 Money spent by Exxon Corporation subsequent to EVOS (in millions of dollars) (11, 155)

Immediate Costs (1989, 1990)	
Cleanup	$2,000
Fishermen	300
Out-of-Court Settlement (1991–2001)	
Damage assessment	214
Habitat protection	375
Administrative costs	35
Research, monitoring and general restoration	180
Restoration reserve	108
Accumulated interest less Court fees	12
TOTAL	$3,224
Civil Trial (1995)	
Compensation to fishermen	$287
Punitive compensation (under appeal)	5000

A $5 billion punitive award has been assessed for Exxon but is currently under appeal (162). The legal costs, ongoing and difficult to ascertain, must also be enormous. For instance, in the first two years after the spill, the State of Alaska alone spent nearly $20 million on litigation (107a).

Although much of the oil is now gone, EVOS remains by far the largest spill in US coastal waters and is unquestionably the most expensive. From Exxon's perspective, the $3.2 billion expended to date on all phases of cleanup, damage assessment, and restoration has increased the value of a spilled barrel from $15 to $12,000 (164). For scale, the same $3.2 billion would, at FY 1995 rates, support the National Science Foundation's programs in General Ecology for 227 years, Ecosystems for 192 years, or Biological Oceanography for 128 years. We believe basic science was shortchanged, and that remediation, restoration, or management protocols will not have been substantially improved for any high-latitude rocky shore coastal systems.

POLITICAL AND LEGAL CONSTRAINTS ON US OIL SPILL RESPONSE

Current legislation discourages research into the consequences of oil as a pulse perturbation for two reasons. First, laws demand that effort be channeled into wildlife rehabilitation, while more effective means of mitigating or preventing spills are not required. Second, legislation requires that oil corporations pay for any damages caused by a spill, which created a situation in which government scientists had incentive to prove injury occurred, while Exxon scientists looked for countervailing evidence.

Major legislation, especially the Federal Clean Water Act (CWA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) dictate federal guidelines and responsibilities for damage assessment and potential restoration subsequent to oil spills. Of particular note are the regulations requiring the Departments of Interior and Commerce to arrange for the collection and rehabilitation of affected wildlife. Alaska state legislation exists in parallel with, and is compatible with, the federal acts (173). At the time of the spill the Environmental Protection Agency (EPA) had in place, as required, a contingency plan giving details of how scientists, response teams, and administrators should interact. While Federal law assigns supervision of an oil spill in maritime waters to the US Coast Guard (USCG), the option exists for the responsible party (Exxon) to direct the cleanup response. Exxon assumed this responsibility, with the USCG and the Alaska Department of Environmental Conservation (ADEC) overseeing the Exxon response and cleanup effort (113, 136). By 31 March, the heads of all Trustee agencies had met and agreed on a general course of action, including an initial payment by Exxon. On 28 April a memorandum of agreement was signed by the heads of the major Federal agencies. The State of Alaska refused to sign because "the state felt that it should be the lead trustee" (173). Nevertheless, formal damage assessment began with this action.

At the outset there appears to have been a spirit of cooperation among corporate and State and Federal agencies, as indicated by shared overflights, maps of the oil trajectory, and mammal and bird rehabilitation. However, conflicts within the agreed-upon administrative infrastructure developed rapidly. A major contributor was a confidentiality restriction placed on all government scientists by the Department of Justice (173). Exxon scientists were similarly gagged by the Corporation (166, p. 118). All accounts agree that the impending litigation both directed research and hampered the development of cooperative efforts, and that the activities rapidly polarized themselves into cleanup/restoration (Exxon) and damage assessment (Trustees). The research performed to test for spill effects was driven by legal definitions of injury, baseline, and recovery.

Injury

According to the Code of Federal Regulations (CFR), injury occurs when there is a "measurable adverse change, either long- or short-term, in the chemical or physical quality or the viability of a natural resource resulting either directly or indirectly from exposure to a discharge of oil..." (43 CFR §11.14 (v)). In the event of injury, the responsible party must pay compensatory damages. Establishing that injury has occurred depends on knowledge of the status of the resource just prior to the spill.

Baseline

In the legal context of damage assessment, baseline is defined as the condition or conditions that would have existed at the assessment area had the discharge of oil not occurred (43 CFR §11.14 (e)). In practice, though, legal proceedings have recognized that these ideal baseline data are unlikely to exist—precisely because some anthropogenic change has occurred—and that various approximations will have to be used. Additionally, as all damage assessments have been settled out of court, no judicial precedents exist on the appropriate or standard uses of baseline approximations or inferences. Rather, in each case, baseline data have been used to influence the outcomes of negotiated settlements.

Recovery

The Code of Federal Regulations defines recovery as a return to baseline conditions (43 CFR §11.14 (gg)). However, two distinct perspectives on the definition of recovery following EVOS developed: that of the Trustees and that of Exxon. In their 1993 Draft Restoration Plan, the Trustees state that a resource will be restored once it has recovered to where it would have been had no oil spill occurred (152). Their 1994 restoration plan does not give an explicit general definition but describes recovery objectives for each injured resource (154). Criteria can include one or more of the following: a return to pre-spill conditions; establishment of conditions comparable to those within unoiled areas; establishment of conditions that would have prevailed had the spill not occurred (i.e. baseline); stable or increasing populations (though in some cases populations were decreasing prior to the spill); or the public perception that the resource is restored. For example, the criteria for the recovery of the intertidal are the return to baseline conditions of community composition, population abundances, age-class distributions, and ecosystem function and services.

The above perspective contrasts that of an Exxon-funded review: "Recovery is marked by the re-establishment of a healthy biological community in which the plants and animals characteristic of that community are present and functioning normally" (9). Explicit caveats are added that age structure or species composition may be different from what it was before the damage, and that it is impossible to determine whether a recovered community is the same as one that would have existed had the spill not occurred.

The Trustees' requirements seem idealistic and unattainable, because, as recognized by Exxon, natural variability makes it impossible to know what a population or community would have been like in the absence of the spill. Nonetheless, judging recovery solely by criteria of ecosystem function minimizes the significance of specific biological detail such as species density and age structure.

POST-SPILL RESEARCH: GENERAL PROBLEMS

Spilled oil is a pulse perturbation. In ecological experiments, pulse perturbations involve altering an extrinsic factor or the density of a species. Subsequent observations serve to evaluate the dynamics of a complicated system. Thus, the *Exxon Valdez* Oil Spill was a sort of unnatural experiment in Prince William Sound. Experiments designed to test hypotheses have the following qualities: (*a*) samples taken before and after the perturbation; (*b*) manipulated (experimental) and unmanipulated (control) treatments; and (*c*) sufficient replication. EVOS generally violated all these requirements.

EVOS: The Imperfect Experiment

It is easy to imagine why EVOS fits poorly into the framework of a rigorous experiment. For most species, there were no "before" samples. If samples did exist, they often were collected in the distant past, suffered from low sample size or high natural variation, or showed populations in decline prior to the spill. The prior studies that did exist can be grouped into (*a*) irregular counts of some of the more conspicuous species, (*b*) annual information about fisheries, (*c*) a few ongoing research projects on orcas and birds, and (*d*) rapid assessment of intertidal areas in PWS and along the Kenai Peninsula where oil was predicted to land.

Research after EVOS also involved comparisons of oiled and unoiled sites. However, since the oil primarily affected the southwestern portion of PWS, most oiled sites were in one region. Because control and experimental sites were not interspersed or randomized, shared conditions other than oil might spuriously distinguish them. The only chance to do a proper experiment would have involved the application of cleanup technologies such as hot water washing or bioremediation, with similar untreated beaches as controls. However, this opportunity was lost early on due to ubiquitous but often unrecorded cleanup activities sponsored by Exxon (166).

Compounding the design problems of this unnatural experiment are several statistical issues. Many tests looked for effects of oil on multiple dependent variables (e.g. population changes of many bird taxa, or lesions in a dozen seal tissues). In general, a treatment effect is termed "significant" when the likelihood is less than 5% that a given difference is due to chance. If multiple dependent variables are examined, 5% will likely show "significant" change even in the absence of a perturbation, and the hypothesis of "no effect" will be rejected when in fact it should be accepted (Type 1 error). For example, growth of 86 bird populations was compared in oiled and unoiled parts of PWS. Two of these populations (golden eye and merganser), i.e. 2.3% of the cases, showed slower growth rates at oiled sites—it is difficult to tell if this was caused by chance, or by the oil. Exxon scientists made similar counts of many bird species to assess whether birds tended to avoid oiled areas using an extremely liberal measure ($p < 0.2$) of "oil effect" (30).

Type 2 errors, in which a hypothesis that is false is accepted, are just as misleading. For those parties interested in proving "no effect" of oil, all that is required is low replication of samples. Bayesian statistics (72) and power analyses (26) reduce the possibility of committing type 1 or type 2 errors, although they cannot overcome the limitations of small sample size. In Bayesian analyses, data are used to distinguish among several alternative hypotheses. If "significant effect of oil" and "insignificant effect" are equally likely, then insufficient data have been collected.

Second, difficulties arose in separating correlation from causation, that is, in determining whether post-spill changes were due to oil or to some other factor. We provide two examples: 1. Some population trends in Prince William Sound are too dramatic to question. From 1983–1988 herring spawned along 106–273 km of PWS shoreline. These values did not change immediately after EVOS (1989: 158 km; 1990: 182 km) (164). In 1994, only 12 km of shoreline received herring spawn, signaling a crash in stocks that prompted complete closure of the fishery (55). There may indeed be latent effects of oil now preventing recruitment and reducing survival, but an alternative explanation, involving competition and predation from hatchery salmon, is also plausible. 2. Few studies (but see 166) have mentioned the possible consequences of a weeklong freeze in late January 1989, when Valdez recorded its coldest day ever measured (156). The freeze was part of a record-setting cold that appeared general across the south coast of Alaska and could have caused substantial mortality prior to EVOS; thus possible oil effects are confounded by a natural calamity. In general, a strong case that correlation is in fact causation requires likely biological explanations for the timing of events (e.g. 22) and experiments demonstrating a mechanism.

Perhaps the most insidious problem associated with detecting effects stems from the natural variability of biotic assemblages. Below we discuss two specific illustrations of the generic difficulty with detecting "injury" in natural communities in the face of tremendous background temporal and spatial variation.

Resampling After Long Intervals

Many of the pre-spill data available for PWS stemmed from studies done in the 1970s and 1980s. In species such as marbled murrelets, Steller sea lions, and harbor seals, it was well accepted that populations had likely declined by 50% in the decades prior to EVOS. It would have been possible, in the absence of intervening information, to ascribe all of the decline to oil effects.

Without baseline studies that focus on potential spill sites, target appropriate species, and involve extensive replication and continuous data collection, it is very difficult to document the effects of a perturbation. To examine these difficulties, we resampled after nearly 20 years a baseline study site in Washington state (120, 121), returning to the same area (within a few meters) and tidal level, at a comparable season, and employing identical procedures (four 0.5×0.5 m quadrats). The resident biota overlaps substantially with that characteristic of Prince William Sound, and because the area is in a vigorously protected nature reserve, we expected little change. In fact, only 2 of 15 common taxa showed significantly different abundances in 1995 compared to the 1970s, based on a 1-way ANOVA in which data were partitioned into past (with nested sample periods) and current times. One of these taxa, ulvoid algae, is highly opportunistic, fast growing, and ephemeral, and its life history makes it a poor candidate for judging biotic change (Figure 3). However, those species showing no statistical change in abundance were not necessarily invariant. Rather, the low sample size, combined with high spatial (within years, e.g. *Balanus glandula*) and temporal (between years, e.g. *Fucus gardneri*) variation caused estimates of abundance to embrace possible extinction in 10 of the 15 species. It would be extremely difficult under these circumstances to demonstrate harm—to show that a sample is an outlier and differs from what would have been expected without the perturbation. Clearly, detecting population change requires numerous samples, distributed through time, focusing on long-lived species. The 5–10 replicates per tide height per site used by most intertidal research teams after EVOS may characterize the intrinsic variability of intertidal biota insufficiently (60, 71, 76).

Modelling Effects of Seasonality and Organism Interactions

Many intertidal organisms in Prince William Sound including mussels, barnacles, and algae exhibit strong seasonal patterns of recruitment, growth, and mortality. In addition, such organisms show marked age/size structure and susceptibility to predation. Given this, what difficulties might arise in determining the population trajectory through percent cover estimates made in different seasons? In a model designed to explore this question, we assume an initial recruitment of mussels onto bare substrate. We obtained size-specific growth parameters from the literature (142, 143) and examined changes in percent cover over a range of size-dependent mortality estimates representing either natural or spill-related changes in predatory dogwhelk numbers (133). Figure 4 suggests that population decline (as an index of "recovery") could result from normal dynamics and not chronic oiling effects. In addition, monitoring studies focused on percentage of cover must be sensitive to the difference that can be produced by just a few months seasonal displacement in sampling. For example, percent cover estimates in April (month 0) immediately after mussel settlement would reveal no differences between sites with the maximum and

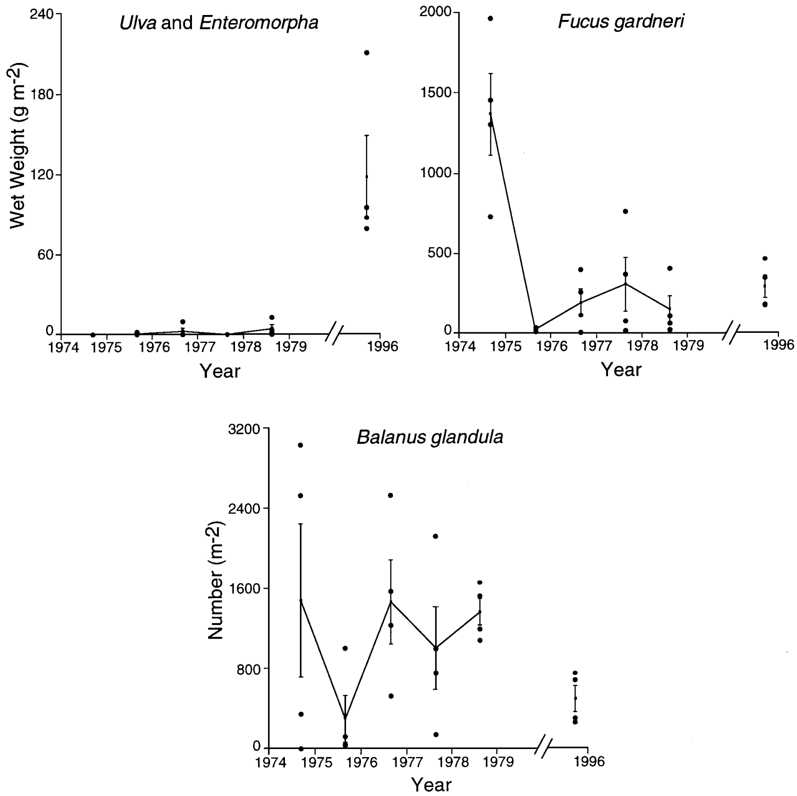


Figure 3 Densities of taxa sampled at Cantilever Pier, San Juan Island, Washington (48°33′N 123°W), for five years in the mid-1970s and again in September 1995. (*a*) Ulvoid green algae (i.e. *Ulva* and *Enteromorpha*), (*b*) *Fucus gardneri* (perennial brown alga), (*c*) *Balanus glandula* (barnacle). Circles represent actual samples. Bars represent standard errors of the means.

minimum predator density; samples six months later (October) would find a 28% difference, and nine months later (January) a 47% difference. Finally, the same proportion of cover at different times or sites may reflect very different underlying predator-prey dynamics. As in all monitoring studies, site-specific sampling data, and the conclusions drawn from them, will be rendered more variable by interactions.

POST-SPILL RESEARCH: CASE STUDIES

The various interested parties were able to agree on only a few findings: The path of the spill, for example, is substantiated by detailed maps (56) (Figure 2).

However, even fundamental "facts" are disputed. Exxon estimated that roughly 36,000 metric tons (10.8 million gallons) were spilled; ADEC's official estimates were 37,333 metric tons (11.2 million gallons), an 11% discrepancy (96). Similarly, estimates of the proportion of the region's shoreline impacted ranged from 10% to 18%, variation that enters from disagreement over the spatial boundaries of the region and the fractal nature of shorelines (166). The biological effects of the spill met with even less agreement.

Table 2 summarizes research done on a variety of species. The morgue counts represent the number of corpses found and attributed to oil, although caution is warranted in accepting either species identifications or cause of death. For example, only 4 of 12 corpses identified as yellow-billed loons and later reexamined, turned out to be that rare species (S Rohwer personal communication). Extrapolations to total deaths were based upon the proportion of tagged and released carcasses found again. From previous studies, it is clear that retrieval generally increases with the number of corpses released, while it

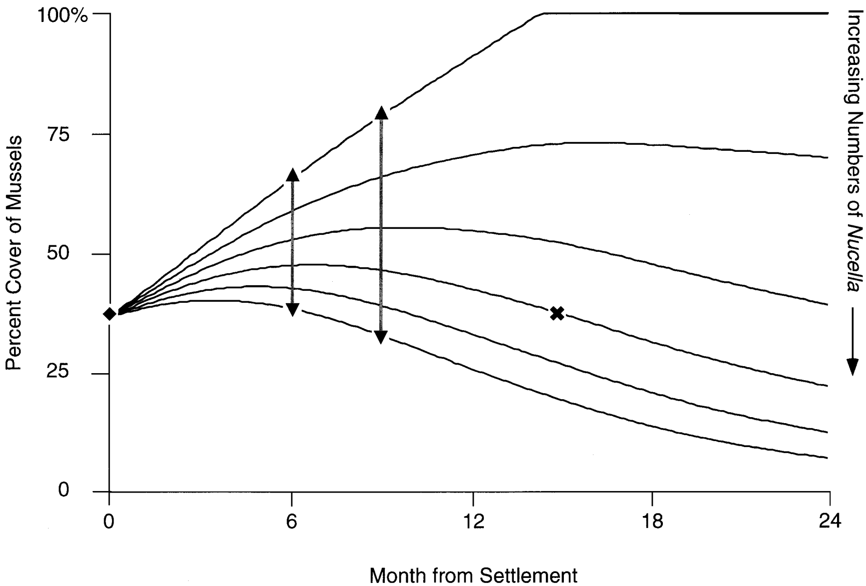


Figure 4 Model results for a scenario in which mussels recruit annually and die from both natural mortality and predation by dogwhelks (*Nucella*). Vertical arrows show that percent cover of mussels 6–9 months after settlement depends upon the density of dogwhelks present. For any given density of dogwhelks, mussel cover varies over the course of the year, although samples obtained at particular times may indicate unchanging cover ♦ and ×.

remains variable (0–59% recovery) due to local conditions (135). At least three corpse-drift studies were performed after EVOS (of 100, 94, and 144 birds), with recovery rates of just 2–3% (41, 135). Corpses also disappeared, once beached, through sand burial and scavenging (41). Radio-tagged carcasses had an average beach tenure of just 24 h (54), and 0–100% of (chicken) corpses were gone within 10 days (171). While the fates of corpses confounded estimates of total mortality, post-spill injury was also examined through censuses of population change and observations of reproductive success. Tissue samples were collected from numerous species to assess toxicological effects of oil.

Many organisms died as a consequence of oil, due to toxicity, hypothermia, or smothering. Their corpses stand as an incontrovertible sign of damage, although separating natural from oil-related mortality and translating corpses into total organisms killed were clearly difficult. Sublethal effects of oil were also evident after the spill. Some organisms such as mussels and seals stored hydrocarbons directly. Vertebrates were able to detoxify oil, but an oil signal could still be detected in bile (oil metabolites) and liver and brain (lesions). Few of the studies done in Prince William Sound to assess changes in population density or demography gave incontrovertible evidence of an oil effect. For example, the productivity of black oystercatchers was estimated to have been reduced by 6% throughout the Gulf of Alaska during the year of the spill, but this calculation was based on 9 corpses, and on poor nestling survivorship in oiled areas of one island (144). The conclusions seem particularly uncertain in light of the fact that nest failure due to predation varied by 20% among oiled and unoiled areas—perhaps the oiled beaches actually kept predators away. In general, spill effects could not be separated from the consequences of cleanup activities and tended to dissipate after a few years.

We have chosen to examine in greater detail the research conducted on a few species to illustrate both problems with the data and the conflicting interpretations of Exxon and Trustee scientists.

*Orcas, or Killer Whales (*Orcinus orca*)*

Orcas highlight the fact that even when exceptional baseline data are available about population size, demography, and individual traits, it may be difficult to show that any changes after EVOS are due to that particular perturbation. Cetaceans are not uncommon in PWS, and orcas have been studied there since at least 1977. By 1987, 221 individuals in seven resident pods or matriarchal groups had been photographically identified by distinctive color patterns or scarring (103). The post-spill study was apparently funded only by the Trustees, and not by Exxon, in contrast to research on many other taxa.

Resident orca pod AB contained 35 individuals in 1984. Between 1984 and 1989 there were 8 suspected mortalities (that is, disappearances with no

Table 2 Highlights of organismal research after the Exxon Valdez oil spill. In 1989, over 50 Natural Resource Damage Assessments were funded for research on birds, mammals, fish and shellfish, and coastal habitats. Some funded studies were not performed (e.g. passerines, migratory birds); some found few individuals to analyze (e.g. sea urchins, cetaceans); some were discontinued after a year, while priorities shifted from damage assessment to restoration. Data are also available on other intertidal (e.g. limpets, *Nucella* spp., barnacles) and subtidal (e.g. helmet crabs, leather and sun stars, eelgrass, kelps) species (31–33, 71, 76, 84). Standard font = Trustee-sponsored research; *italics = Exxon-sponsored research.* n = Number of sites (or individuals if noted by “indiv.”). B = data before spill; A = data after spill; U = data from unoiled site; O = data from oiled site; T = data from treated (e.g. cleaning attempted) site; L = data from lightly-oiled site; M = data from moderate to heavily-oiled site; H = hydrocarbons. Morgue counts refer to total numbers of carcasses of each taxon found after EVOS in the entire spill area (or in PWS if noted). For multiple comparisons, only significant differences have been included. > and < signs represent significant differences that may or may not be due to oil.

SPECIES	MORGUE COUNT	ESTIMATED DEATHS #{% of exposed population}	POPULATION CHANGE	DEMOGRAPHY	TOXICOLOGY	REF.
All whales	37 strandings in ’89 (A = B)				tissue (’89): no H (n = 7 stranded indiv.)	98
Humpback	no strandings in ’89		density (’89–90): A < B (’88), due to wider search	reproductive rate (’89, 90): A = B (’80–88)		161
Orca	strandings (’90): 3; (’92): 1		pod AB (’88–90): 13 of 36 gone; other pods: 0 gone; transients: 9 gone			28, 103
Steller Sea Lion	12; 16 killed for tissue samples	not oil-related	population decline (’60–’90): 70%; (’89): A = B	# pups: O = U; ’89 < ’90; premature births: O > U	bile H metabolites (’89): high; lesions: none	26
Harbor Seal	18; 27 killed for tissue samples	300 {36%}	population decline (’75–’90): > 10%/yr; (’89): O (n = 7) > U (n = 18)	pups / total: (O) ’89 < ’90; (U) ’89 = ’90	bile, brain, blubber H (’89): O (n = 13) > U (n = 14 indiv.); brain lesions: 35 d post-spill (n = 1) > 3 mo. (n = 11 indiv.)	51–53, 147

Sea Otter	1011; 493 in PWS	2800–4028	census ('89–'91): (O) A < B ('85), (U) A > B; *census ('91): A = B ('85) (n = 3)*	prime age animals as proportion of deaths ('89–91): A > B; *reproduction ('90, '91): (O) A = B*	tissue H ('89): O (n = 10) > U (n = 12 indiv.)	10, 16, 24, 44, 58, 85, 114
River Otter	few		latrine site abandonment: O > U; scat decline ('90): O > U	weight ('90, '91): O < U; ('92): O = U	blood haptoglobins : ('90, '91) O > U; '90 > '91 > '92	37, 38, 166
Bald Eagle	151	902 {11%}	census ('89–91): A > B ('82); *habitat use (to '90):* O < U	nest failure ('89): O (cleanup?) > U; survival of tagged birds (8/89): O = U; *density ('90, '91): O > U; nest success ('90): O = U, ('91): O > U; young/nest ('90): O = U; ('91): U > O*	blood ('89, '91): H low; uric acid: H depend on recent food	19, 30, 167
Peregrine Falcon	no known deaths		40–60 prs in spill path	nest productivity ('89): O (n = 13) < AK in general		79
Marbled Murrelet	289 in PWS; 334 total murrelets	5000 {1.25%}	density ('73–'85): decline in PWS; census ('89): A < B ('78–80); ('90, '91): A = B; negative correlation between boat/air traffic and density	juvenile-to-adult ratio ('89): O (n = 3) < U (n = 1)		27, 90, 135
Kittlitz's Murrelet	72 ≥ 100	1000–2000 {5–10% of species}				159, 160

(*Continued*)

Table 2 (*Continued*)

SPECIES	MORGUE COUNT	ESTIMATED DEATHS #{% of exposed population}	POPULATION CHANGE	DEMOGRAPHY	TOXICOLOGY	REF.
Common Murre	21,604; 438 in PWS	375,000–435,000 {50–90%}	census ('89–91): A > B; *density: A = B (Barren Isl.)*	breeding date ('89): A later than B; *attendance ('91): A = B*		43, 49, 68, 122, 129, 134, 135
Pigeon Guillemot	135 in PWS	{% of 5000}	density ('72–'85): decline by 50%; decline ('89 vs. '85): O > U; *habitat use: ('89–91): O = U*	hatching, fledging, feeding rates & fledging weights ('89): O = U (n = 1); chick weight, hatching success: '89 > '90		30, 66, 91, 123, 135
Storm Petrel	12 in PWS; die-off in Aug. 89		density ('89): A = B (Barren Isl.)	reproductive success ('89): A = B		119, 135
Black-legged Kittiwake	123 on beaches		*habitat use: ('89–91): O = U*	chicks / nest ('89): A < B ('85–88); ('90–92) O (n = 10) & U (n = 14) decline	oiled feathers ('89): ≤37% of birds; liver ('89): H in of 10 indiv.; ('90) H in 0 of 5	30, 80, 171
Glaucous-Winged Gull	52 total gulls in PWS		*habitat use (to '90): O < U*	breeding pairs, nest density, clutch size, hatching success, fledging success ('89): A = B on island 25 km from spill		30, 130, 134
Harlequin Duck	148 in PWS	423 {of ≫ 2000 total }	*habitat use (to '91): O < U*	pairs/stream ('91, '92): O (n = 16, 37) < U (n = 12, 20)	oil metabolites in bile ('89): O > U	30, 131

Goldeneye	64 total goldeneyes			population increase ('90–94): U>O		2, 131
Merganser			*habitat use (to '89 or '91):* O < U	population increase ('90–94): U>O		2, 30
Oystercatcher	9	120	census: O < U; *habitat use (to '91): O < U*	chick growth, survival, feeding rate ('89): O<U; hatching success: O = U; nest predation: O < U (n = 1 pr)		30, 144
Cormorant	461 in PWS					131
Yellow-Billed Loons	87; 395 total loons in PWS	300–900 {6–18% of AK population}	density ('89): A = B ('83, '84) (n = 1)	% nesting ('89): A < B		48
Pink Salmon	no known deaths		hatchery stocks at record levels; many wild stocks low	egg mortality ('89–91): O > U; egg to fry survival: O = U; growth: O (low temperature) < U; *egg viability ('89–91): O = U in lab; adult return: O = U*	lesions in larvae ('89–91): O > U; H in bile (n = 5 individuals)	21, 23, 89, 101, 139, 141, 168, 169
Dolly Varden fish	no known deaths			survival ('89, 90): O (n = 2)<U (n = 3); growth: O (n = 2) < U (n = 3); uncertain because 47% "evaded recapture"	liver lesions: O (n = 1) > U (n = 3)	69, 102
Herring	no known deaths		length of spawn ('89–90): A = B; ('94) A ≪ B ('83–88)	40% (*4%*) of spawn area oiled; egg mortality: O > U; hatching rate ('92): O (n = 1)<U (n = 1); *larval hatching: no relation to H*	egg, larval abnormalities ('92): O > U; *larval abnormalities: no relation to H*	14, 55, 88, 132
Rockfish	5				lesions ('89, by species): O > U	102, 104

(*Continued*)

Table 2 (*Continued*)

SPECIES	MORGUE COUNT	ESTIMATED DEATHS #{% of exposed population}	POPULATION CHANGE	DEMOGRAPHY	TOXICOLOGY	REF.
Shrimp (*Pandalus*)		*catch ('89–91): A < B ('80–88); larvae: '89 > '90*	female density ('89): O (n = 3) < U (n = 3)	dead eggs in females ('89): O > U; *fecundity* ('89–91): *O = U*		5, 34
Clam (*Protothaca*)	'89 counts (n = 9 in PWS): few dead clams		density ('90–92): T (n = 4) < O (n = 5) = U (n = 3)	growth ('89): T = O = U; growth ('91): high sediment H < low H		35, 76
Snail (*Littorina*)			density ('90): O < U; ('92): T > O = U	size ('90): T (n = 4) = O (n = 5) < U (n = 5)	tissue H: T (n = 9) > O (n = 7) > U (n = 7)	71, 76, 77
Mussel (*Mytilus*)			density: O = U; O = U = T; *density: L = M = U*	growth ('90): T = O > U; mortality ('90): T = O < U	tissue H: T > O > U; *tissue H:* '89 > '90 > '91	17, 60, 71, 76, 77, 105
Rockweed (*Fucus*)			large plant density ('90): U > O; ('93): O > U; density ('90): T < O = U; ('92): T = O = U; *density ('90): L < U = M or M > L = U*	reproduction: O < U		60, 71, 76

subsequent resurrections) and 9 calves survived to an age of at least 6 months. Thus in September 1988 there were 36 whales in this pod; on 31 March 1989 only 29 were observed and an additional 6 whales disappeared between then and June 1990. Calculated annual mortality for these two years was 19% and 21%. There were no births during this interval.

Because orcas survive to an age of 80 or more years and live in small family groups, pod-specific mortality rate estimates can be vexed by small sample sizes. A larger data set garnered over a 17-year interval in Puget Sound, Washington, and British Columbia suggests that a pod of 29 members has only a 2.3% chance of losing >6 members in a year (28, 124). Because six other resident PWS orca pods show no evidence for accelerated mortality during this interval, and because no corpses were recovered, attributing the disappearances to oil remains speculative (28).

Another source of uncertainty is the hostile interaction between a sablefish fishery and these whales. Many whales have been shot, and bullet wounds have been identified in both photographs and corpses. Such an alternative potential mortality source also makes any conclusion about an EVOS effect scientifically insupportable despite the unusually detailed prior database.

*Sea Otters (*Enhydra lutris*)*

Both Exxon- and Trustee-biased accounts agree that sea otter populations were numerically and visibly impacted. Because they represent prototypical charismatic megafauna, they became immediately symbolic of the destructive effects of a massive oil spill. Money flowed towards them: $18.3 million for capture and rehabilitation (44) and $3–4 million for damage assessment and research (148).

Commercial exploitation from 1741 to 1911 drove otters close to extinction before they were granted federal protection. The PWS population probably represented a remnant (93): It is estimated to have grown 9% per year until 1989, when 6500 otters were thought to have inhabited the oiled area (58). They thus represent a species for which pre-spill data suggested a growing local population.

The impact of EVOS on otters is evident from morgue counts. Intensive beach surveys collected 871 otters dead from oil or natural causes (493 in PWS) (10, 148). Another 357 were captured and delivered to rehabilitation centers: Of these, 197 were eventually released, and 25 were transferred to permanent holding facilities. Estes (44) calculated that the cost per saved otter exceeded $80,000, and he concluded that great expense, high mortality of oiled individuals eventually released, and a 5–10% mortality due to the stress of capture of even healthy otters renders such humanitarian efforts ecologically “unrealistic.”

In the case of otters, prior data provide convincing evidence of population decline due to oil. A pre-spill census conducted by boat in 1984–1985 involved 742 shoreline transects (822 km^2) (81). This heroic effort estimated a density of 5.12 ($\pm$ 0.12 SE) otters/ km shoreline. Comparable post-spill sampling in 1989–1991 yielded significantly lower densities with no sign of recovery (July 1989: 3.30 [($\pm$ 0.42 SE); July 1990: 2.76 ($\pm$ 0.47 SE); July 1991: 2.91 ($\pm$ 0.34 SE)] (24). Otter abundances remained depressed at least through 1993 (1).

In contrast, Exxon scientists found that otter densities at two of three sites were indistinguishable from prior censuses, and at the third site otters recovered to pre-spill densities by 1991. In order to resolve unchanged population densities with known deaths, the otter population was hypothesized to have increased in the time between pre-spill censuses and EVOS. As further indications of complete recovery, Exxon scientists found that otters produced just as many pups one to two years after the spill as they had before, even at heavily oiled sites, and otters used oiled areas just as frequently as similar unoiled habitats (85).

Within PWS as a whole, sea otter populations are probably increasing today, although doubt may remain about the time course to recovery because of both chronic effects of oil (111) and possible disease introduction from the intensive rehabilitation efforts (110). However, many millions of dollars appear to have been squandered as the antagonists jockeyed for legal advantage, and little seems to have been learned of significance for the conservation, restoration, and especially management of this ecologically conspicuous species.

*Bald Eagles (*Haliaeetus leucocephalus*)*

Both Trustee (19) and Exxon (167) biologists agree on some basic facts: About 150 eagle carcasses were recovered in 1989; most of the 1989 damage was due to a negative effect of the massive cleanup effort on breeding birds; no post-spill oil-related effects were visible in 1990 and 1991. Another 137 birds were captured, cleaned, and released, at a cost of approximately $10,000 per bird (166). We focus on the body count to make the following general point. Mortality from the spill should add to that occurring naturally. This was the most convincing argument presented by orca biologists that pod AB was probably damaged by oil: Observed post-spill mortality was greater than expected under normal conditions. For eagles, however, this type of reasoning was not applied. Spies (146) refers to the 150 carcasses as “unequivocal evidence of the impact.” Other Trustee biologists (19) have applied standard factors to adjust for unrecovered corpses and increased the estimated mortality to 614 to 1871 eagles, with a best estimate of 902 deaths or 11% of the 8000 eagles thought to live in the vicinity of the spill. No one developed a model of null expectation: How many eagle corpses might have been found in an intensive search of the area in any other year, especially after an exceptionally cold winter? Maximum known longevity for this species is 22 years (15), which generates a minimal death rate for adult eagles of 5% yr^{-1}, or 400 birds in the spill trajectory. A more reasonable life span of 10–15 years would result in a higher natural mortality rate. Since eagles feed and nest in the marine near-shore environment, dead eagles are likely to be deposited along coastlines. We may not need to invoke EVOS to explain a retrieval of 150 corpses from 800 km of searched shore, or 328 extrapolated to the entire spill trajectory of 1750 km.

*Murres (*Uria *spp.)*

Murres are abundant, colonial-nesting seabirds in PWS and waters adjacent to the oil trajectory. They accounted for about 74% of the vertebrate carcasses recovered up to August 1989. This body count (21,500 birds) is the only reliable fact underlying subsequent reconstructions of mortality (135). Controversy centers on how to estimate both the actual number of murres killed and the post-spill impacts on colony breeding success (129, 134, 135). Trustee biologists have extended the minimal mortality estimate by considering whether carcasses sink or float, whether oiled murres swim toward or away from land, and the potential role of scavengers. One recent estimate was that 375,000 murres died, of which approximately 6% were initially recovered (134). Exxon scientists argue for interpretive caution since no reliable estimates exist for pre-spill murre population numbers in the impacted region, and even in the best-studied site (Barren Islands) "the various estimates varied by 80,000 murres within a two-year period" (129). Certainly the body count represents the absolute minimum mortality, but the percent of murres killed by oil, the breeding colony to which they could be assigned, and even the possibility of a 1 to 2 year decrease in reproductive effort and colony success all remain conjectural. The continuing debate about the "facts" strains the credibility of all biological inferences. At the worst, sensationalized accounts of the event, tending to err on the high side, have made their way into textbooks (108), adding yet another layer of misinformation.

*Kittlitz's Murrelet (*Brachyramphus brevirostris*)*

Our concern here is an inability or unwillingness of agencies to focus on rare or seriously threatened species. Rarity of a species suggests that a priori data are few, and that quantitative assessment will be difficult; it also implies a high susceptibility to natural or human-caused catastrophe—all traits that predispose the species for federal listing. Kittlitz's murrelet is a small seabird whose world population is estimated at 18,300, 95% of which survive in Alaskan waters (159). Its biology is tied to coastal glaciers by breeding in the high alpine zone and foraging in glacially silted freshwater plumes. The 30,000 km^2 area impacted by the oil represented a core area for its breeding, molting, and feeding, and this area contained approximately one half of its known population (160). Thus Kittlitz's Murrelet seems especially susceptible to high latitude coastal spills such as EVOS.

Of the 34,977 carcasses logged in a US Fish and Wildlife Service database, only 67 were of this species (41). However, when impact is defined as the proportion of the total world population killed by, or disappearing after, some catastrophic event, direct mortality for this species may have been as high as 5–10% . In general, rare species and most transients, e.g. migratory waterfowl, shorebirds, and land birds foraging in the intertidal zone, seem to have been ignored.

*Pink Salmon (*Oncorhynchus gorbuscha*)*

Pink, or humpback, salmon, a commercially valuable species worth well over $50 million annually, has been carefully monitored for many years in Prince William Sound (100). Highly variable annual catches ranged between 10 and 30 million fish in the eight years prior to EVOS (139). Population fluctuations, migration, growth, and survival are tracked by marking hatchery fish with coded wire tags before their release as juveniles.

Pink salmon have a 2-yr life cycle, where the first year is spent developing in the intertidal and nearshore environment, and the second year is spent in the northern Pacific, with a final return to the shore. There are no data on immediate oil-induced mortalities, but several generations were exposed to oil. Exxon scientists showed that eggs collected from oiled and unoiled streams hatched equally well in the lab [91.1% vs. 90.6% (21)], whereas a Trustee-sponsored field survey of 31 streams found significantly higher egg mortality in oiled than in unoiled streams in 1989–91 (23). Coded wire tag data indicate that juvenile growth rates were significantly lower in moderately oiled hatchery areas than in lightly oiled areas in 1989, although low water temperatures confounded oiling (170).

These lower growth rates were calculated to reduce juvenile survival in 1989 by about 2% at three hatcheries. Nevertheless, the 1990 harvest set a PWS catch record with over 44 million fish. This dramatically high catch has been attributed to unusually favorable weather conditions and a record-setting plankton bloom that served as food for the juveniles in 1989 (140). The 1991 catch, 37.3 million salmon, was the second largest catch in PWS (139). In 1992 and 1993 the catch fell to below 10 million fish and then bounced back up to over 30 million in 1994 (141). Despite the wealth of long-term (several decades) baseline data available, it remains difficult to identify population effects of EVOS, or delayed changes mediated through indirect effects, because of the high population variability that exists naturally.

*Rockweed (*Fucus gardneri*)*

This perennial brown alga forms a major, biologically important zone in PWS and throughout its broad geographic distribution; it may be the single most significant species at mid to high levels on rocky intertidal shores in terms of biomass (71). *Fucus* was severely impacted by both the oil from EVOS and the high pressure hot water cleanup (92). It was studied using funds from Exxon, Trustees, and the National Oceanic and Atmospheric Administration (NOAA).

The response of *Fucus* to oil on other high latitude shores has been followed closely (65, 145). *Fucus* colonized bare rock about six months after the 1967 *Torrey Canyon* spill and persisted for five years before a combination of natural senescence and unusually high densities of limpets eliminated almost all algal cover. Populations of limpets subsequently crashed from lack of food. Cycles of algal recruitment and disappearance persisted for at least a decade (65).

In Prince William Sound the fate of *Fucus* was used as an index of intertidal recovery. Exxon scientists, focusing on plant biomass, claimed that most of the *Fucus* zone on oiled shorelines had recovered by summer 1990, 15–18 months after the spill (60). In stark contrast, a Trustee-sponsored team concluded that “full recovery has not yet occurred more than 4 years after the spill” (71). This conclusion was based, not on mass, but on population age/size structure, density of reproductive plants, and the number of eggs settling on the shoreline. Additional field experiments (71) and longer term studies (75) in PWS suggest that as the initial *Fucus* cohort senesces after about 6 years, percentage of cover decreases dramatically. Subsequent regrowth of *Fucus* permits the return of grazers. The pattern appears strikingly similar to the grazer-mediated cycles observed after the Torrey Canyon spill (65), and it may exemplify the sorts of dynamics likely after oil spills.

Exxon’s assessment of *Fucus* recovery, based on comparative studies of plant mass in oiled and control sites, is statistically correct yet biologically flawed. Prior consideration of the *Torrey Canyon* results should have fostered a more conservative, longer-term perspective, in which re-establishment of age structure and reduction in biomass oscillations are critical components of recovery. Re-establishment of age structure is admittedly difficult to judge in *Fucus*, as age can be estimated only by size. However, both growth rates and age can be determined in species, from algae to fish, with distinct annual growth increments. Even after a spill, these species can be used to assess whether oil causes unexpectedly high mortality in certain age classes, whether growth rates change in concert with oiling, and the extent of natural variability in species’ growth rates or age structures.

OIL REMOVAL

Although emergency response plans are legislated for all areas with major oil tanker traffic, current containment and recovery techniques are inadequate for large spills (87, 165). Thus, shoreline cleanup and remediation have been important components of oil spill response, and numerous options for cleanup existed at the time of EVOS: burning, washing, scrubbing, booms, dispersants, and detergents. Most of these cleanup techniques, however, have been employed in essentially unchanged fashion for decades, as spill after spill has touched shore. This shallow learning curve can be attributed in part to federal constraints on developing and field-testing novel cleanup technologies (117; but see 42, 47, 138). Although detergents with well-known toxic properties were applied sparingly on PWS shores (65, 118), other high impact techniques, including high-pressure hot-water washing and heavy equipment in marshes, were employed despite warnings from science advisers (95). Sadly, the State of Alaska mandated that oil be removed, rather than taking a scientifically favored focus of minimizing total ecological effects (95). Two of the most conspicuous attempts at cleaning oiled beaches in PWS involved washing and bioremediation.

High-Pressure Hot-Water Washing

High-pressure hot sea water (71°C) was sprayed onto many shorelines from omni-barges even though American Petroleum Institute guidelines recommend "natural cleansing" as the preferred method to remove oil from exposed rocky shores. In fact, high pressure flushing is "not advisable" as it tends to remove organisms and substrate as well as oil (50). Such an outcome was manifest in PWS, whenever both short- and long-term impacts were assessed. The immediate consequence was the removal of an estimated 15% to 27% of the oil from rocks, but flushing also increased the number of dead mussels by 20 times and reduced the mean number of species in 0.25 m^2 quadrats from 8 to 3 (105). The addition of an oil dispersant along with hot water resulted in 75% mortality of clams (*Protothaca staminea*) subtidal to cleaned areas (105). Researchers speculate that the sediment washed out and transported by the high pressure cleaning might have smothered organisms even deeper in the subtidal zone (76). While high-pressure hot water effectively removes oil, it also increases the mortality of organisms that manage to survive the initial spill.

Longer-term consequences were examined by comparing a few (nine) oiled areas that were set aside and not cleaned, with areas that were oiled and cleaned, and areas that were not oiled. Percent cover of rockweed, which reaches 50% on unoiled areas, returned to normal values by 1991 on oiled sites but not until 1992 if those sites were also cleaned (76) (however, remember the age/size caveats above). Cleaning also apparently reduced the diversity of species found in soft-sediment cores for at least 2 years after the spill, while oiled sites that had not been cleaned showed reductions in species abundances but not in diversity (76, 77, 105). In general, cleaning produced more biological differences than oiling, in comparison to pristine sites.

Bioremediation

One of the more promising techniques for post-spill cleanup involves the degradation of petroleum products by microorganisms (6). Hydrocarbon-degrading microbes occur naturally in PWS, but oil disappears more rapidly if these resident consumers can be stimulated to break down oil. Fertilizers were added to oiled shorelines to test whether biodegradation could be accelerated without causing nutrient toxicity or eutrophication of coastal sites. Early results showed clear "windows" of fertilized beach surrounded by oil, and bioremediation was termed a success (137). However, microorganism counts were not significantly elevated by fertilization, nor could any significant declines in oil be detected by gravimetric techniques (e.g. oil per area or volume) (150).

Oil degradation has traditionally been measured using large hydrocarbons as a persistent background against which to judge disappearance of other oil fractions. Because the resident microbes in PWS break down large hydrocarbon molecules, this technique failed until still larger, undegraded compounds were identified. Recent reanalyses show that fertilization accelerated the loss of hydrocarbons relative to unfertilized control areas at one of three sites; none of the sites showed signs of eutrophication (20). The successful fertilization occurred at a site with a high nitrogen concentration to oil load (nitrogen per oil per sediment volume), in which degradable oil fractions were still prevalent. If fertilizer is applied early, bioremediation may reduce oil, but the utility of this approach (i.e. how much additional oil microorganisms remove in comparison to wave action, and whether any intertidal species suffer less as a consequence) is equivocal.

NO USE CRYING OVER SPILLED OIL: FUTURE POST-SPILL RESEARCH

In our estimation, the research initiated after EVOS failed in three ways. First, much of it was carried out to assess injury in terms of changes in population size, using species lacking adequate baseline information. Few significant, unambiguous changes were found, but this is likely due to an inability to detect change rather than to an absence of mortality: Tremendous declines would have been required as incontrovertible evidence of injury when assessed as departures from baselines. Second, opportunities for controlled experimental examination of the effects of various cleanup techniques were lost. The blame for this omission should be shared: public outcry to "do something," NOAA's decision to set aside 9 rather than 61 uncleaned sites (164), and Exxon's failure to keep track of shoreline treatments (166) all contributed.

The third failure involves outlays for restoration projects. Restoration has become the major beneficiary of money still available from Exxon's $900 million out-of-court settlement, but the money seems misdirected in light of available evidence about what components of the PWS ecosystem suffered injury. For example, despite the fact that hatchery-raised pink salmon have reached record returns, and that evidence of negative effects of oil on salmon is disputed, nearly 20% of all restoration funds are being expended on salmon-related projects in 1996 (155). Even at the outset, although partly required by law, much effort went into the rehabilitation of oiled birds and otters, which did little to aid populations, and into beach-cleaning, which arguably did more harm than good. If oil shippers pay for restoration after a spill (either to compensate for damages or as punishment for littering), then these funds would seem best directed toward improving the status of the most rare and endangered species within a system (e.g. Kittlitz's murrelet) and identifying the causes underlying population declines unrelated to spill effects (e.g. sea lions and harbor seals). Foxes introduced to islands as a source of fur have done greater harm to Alaskan bird populations than an oil spill possibly could (8, 25), and moderating this and other anthropogenic onslaughts such as dredging or clear-cutting should constitute a viable "restoration" alternative. In that way, the inevitable next oil spill will be less likely to cause extinctions.

Future oil spill research should (*a*) allow injury to be assessed in a more convincing way, (*b*) incorporate studies of both direct and indirect effects of oil, and (*c*) use the spill as a pulse perturbation to study the dynamics of coastal species assemblages. Our recommendations reflect these goals.

Better Baselines

Although often tedious to collect, baseline data are essential to understand whether an environmental disaster has affected species. The effectiveness of baseline data depends on knowing a species' status immediately prior to the spill and on the ability to detect departures from natural variation. Variability in density measures can be reduced by paying attention to season (e.g. densities vary within a year but may be consistent each summer), species (e.g. long-lived species and local dispersers tend to show less natural variability), and replication, which should be sufficient to overpower statistical variations in local distribution and abundance. In practice, baselines will concentrate on two categories of species: those that people care about, and those that are reliable indicators of change. Baselines need not be simply measures of species abundance, nor are all species equally suitable. In the following sections we discuss the value of understanding natural mortality, demography, age structure, recruitment, zonation, and patch structure.

Better Estimates of Acute Mortality

Deaths are an unarguable sign of injury, but corpses do not reflect the exact number of individuals that died due to oil. Two components are involved: determining what proportion of the corpses represent oil-related mortality, and extrapolating from these corpses to the total death toll. Especially needed are field measurements on the propensity for corpses to sink, float away, or be scavenged beyond recognition. Considering how critical this information is to both damage assessment and litigation, there remains no scientifically justifiable reason to avoid using retrieved corpses to generate data on the fate of organisms killed by oil.

Rapid Assessment

With the development of increasingly sophisticated models predicting oil spill trajectories, it should be possible to mobilize research teams to acquire pre-spill data (50). These data, which might include photographs, species abundances, or marked quadrats, give a view of the shoreline immediately prior to oiling that can be compared to samples after the spill. In the EVOS case, between three days and a week were available for these sorts of rapid assessments, but few were carried out in PWS (but see 135, 166). An assessment attempt along the Kenai Peninsula was foiled when oil failed to land on the stretches of intertidal that had been marked and inventoried (D Duggins, personal communication).

Demography

Whether or not effects show up as changes in species abundance, oil may affect demography, especially age structure, birth rates, and individual growth rates, and consequently a spill could alter population trajectories. For some species, these population metrics may be much more spatially and temporally consistent than density and thus provide a better indication of injury. Data might include pupping rates, adult-to-juvenile ratios, clutch size variation, or even dispersal tendencies. For example, after EVOS, black-legged kittiwakes, harbor seals, and *Fucus* all showed lower offspring production at oiled compared to unoiled sites, although hatching success in black oystercatchers was higher at oiled sites (Table 2).

In many invertebrate taxa, the presence of hard mineralized skeletons allows for assessments of pre- and post-spill demography. Candidate intertidal species in which it is possible to determine the age of individuals include sea urchins [rings in the ambulacral plate of *Strongylocentrotus droebachiensis*

(83)], gastropods [annual growth rings in the shell of Tegula (125) or Protothaca (76)], barnacles, and bryozoans (40). Some algae also show growth rings [in the stipe of *Laminaria* spp. (86); as remnants of each year's blade in *Constantinea* spp. (29)]. In all these species, individuals collected some time after the spill can be backdated to compare pre- and post-spill population age structure and growth rates. Prior reproductive effort may also be accessible for comparison if, as in some bryozoans, external brood chambers persist (40). By experimentally treating individual colonies with vital stains such as tetracycline immediately after a spill, it should be possible to compare pre- and post-spill reproductive efforts.

Recruitment

Demographic data indicate population changes of locally dispersing species, but for many intertidal organisms with long-distance planktonic larval stages, recruitment rather than reproduction has the greatest influence on recovery. A standard method for assessing recruitment is to clear the substrate or attach settling plates and observe what appears on these bare areas. The critical comparison is between oiled and unoiled substrates (plates) placed into oiled, cleaned, and unoiled sites (39, 74). If recruitment differs among sites, then either the proximity of oil or some confounding factor (e.g. currents) is responsible. If plates within sites differ, then oiled surfaces affect recruitment independently of site characteristics.

This technique becomes particularly powerful when combined with grazer-exclusion treatments because most intertidal studies show that limpets, chitons, crabs, and snails determine the algal species that appear in bare spaces (99, 127). An absence of a treatment effect in such a grazer-exclusion experiment would indicate an anomalously low level of herbivory.

Intertidal Zonation

Zonation, the conspicuous layer-cake arrangement of species, might well change after a spill (94). It integrates a wide variety of physical and biological processes into a relatively stable pattern that can be easily tracked photographically (126). In the aftermath of an oil spill, dramatic changes in zonation boundaries would be expected to occur as oil or cleanup kills mobile consumers, sessile invertebrates, and algae. Measuring the time to re-establishment of stable zonal boundaries provides an estimate of recovery time.

Patch Structure

Intertidal mussel beds often display gaps of a characteristic size-frequency and distribution (128). These gaps, or patches, result from disturbance by waves, logs, weather, and predators. A change in the disturbance regime might be expected to change patch structure and thus exert indirect effects on a number of species, since the heterogeneity afforded by patches promotes species coexistence. Oiling kills mussels and therefore creates large patches. Oil effects might also be mediated indirectly through sea otters that consume mussels, since a reduction in otter densities could cause the small patches characteristic of their intertidal foraging to decline in frequency (158).

Replicated Tests of Cleanup Techniques

Thirty years of experience with oil spills on rocky shores have shown that dispersants and hot water cleaning, while removing oil, also kill many surviving plants and animals (59, 65, 118). Nevertheless, there are situations in which cleaning will continue to be carried out: under intense public pressure; in low-energy estuaries and bays where natural oil removal is slow (151); and as chemical companies develop putatively safer cleaners. To determine the effects of various cleaning methods, it is necessary to perform replicated tests, applying the technique to half of a beach and maintaining the rest as a control. Furthermore, both oiled and unoiled beaches should be included in the cleaning, to separate oil effects from cleaning effects. To this end, EPA needs to commit itself to aid the development and testing of cleanup technology, even if this means encouraging carefully planned and executed experimental oil spills.

Food Chain and Indirect Effects

Oil effects beyond direct mortality can be manifest when hydrocarbons are passed from prey to predators, or when oil-induced alterations in the density of one species affect others. A developing controversy involves the passage of EVOS hydrocarbons through marine food chains (7, 13, 36, 63). Since mussels harbor patches of unweathered oil in anoxic sediments around their byssal threads, they can filter these slowly released hydrocarbons for years (7). Mussels are eaten by sea ducks, sea stars, and sea otters, so these and other intertidal foragers remain exposed to oil. Trustee-sponsored scientists have found at least 59 mussel beds around Knight Island that in 1993 still showed elevated hydrocarbons in sediment and mussels (7), although Exxon-sponsored scientists argue that levels are not high enough to make a difference to higher trophic levels (164).

Oil effects may cause—or be obscured by—longer-term indirect effects that propagate through assemblages. In fact, a high proportion of ecological impacts (up to 60%) are transmitted indirectly (106). For instance, otters are known to eat predatory invertebrates such as crabs and sea stars. These species in turn have dramatic effects on barnacles, limpets, and other species not normally consumed by otters, which subsequently affect algae that would never be otter food. Sea otters provided early convincing evidence of these sorts of trophic cascades, where fluctuations are transferred through feeding links (45, 46), and the substantial pulse perturbation of otters in PWS likely generated changes beyond those in otter number alone.

SUMMARY

The evidence that EVOS harmed individual organisms brooks little argument. Despite uncertainty in precise cause of death and the difficulty of determining total mortality from counts of corpses, numerous birds, mammals, and intertidal biota died from oil toxicity, hypothermia, smothering, or cleanup. Furthermore, tissue chemistry and histopathology indicated that individuals living in oiled parts of Prince William Sound suffered sublethal effects, although the manifestation of oil exposure varied greatly among species.

The population consequences of the oil spill have been more disputable, stemming from the difficulty of determining how abundant a species was before the spill, how many individuals actually died, and how these deaths and persistent but unquantified chronic injury would affect future population growth. More consistent baseline monitoring of a few indicator species could allow better determination of whether oil causes fluctuations outside the range of natural variation. Monitoring will, however, be costly. The missed opportunity of EVOS is that little was learned about long-term population response to, or interspecific interactions after, the dramatic pulse perturbation.

Perhaps the harshest lesson of EVOS is that basic science motivated by litigation served no master well. We have documented some of the conflicts stemming from biological research. A more dismal interpretation of EVOS research comes from Barker (11): Scientific evidence became discredited in the jury's eyes as expert witnesses with conflicting testimony canceled each other out.

In a practical sense, we hope that the lesson from EVOS is that preventive measures such as well-rested pilots and double-hulled ships, and a rapid response of burning or skimming spilled oil may eliminate future swaths of destruction. But the unending stream of ugly and toxic spills since 1989 belies any such education. Repeated spills cannot help but turn a shoreline into an asphalt parking lot. When another spill occurs that galvanizes the American public and creates a research agenda, perhaps the punishment can be meted out expediently, and the focus turned from arguing about whether feathered, furry, or edible species have been irreparably harmed to better understanding how processes underlying coastal systems are altered in the face of a massive perturbation.

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