Exxon Valdez
Oil Spill Symposium

Abstract Book

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So Why Can't Science Tell Us More About The Effects of the Exxon Valdez Oil Spill?

Robert B. Spies
Applied Marine Sciences

The Exxon Valdez went aground on a reef within shouting distance of the route which carries 20% of the oil produced within the United States. It took less than 20 years for this experiment to happen. It was not planned, but it was expected, and we should have been better prepared. We can see now that we were not ready for the spill, either for clean up or for assessment of effects. We are all aware of the billions of dollars spent cleaning up the oil. I would like to give you some idea of the consequences of not being prepared to assess the damages, and at the same time provide a primer on the use of different sorts of information in injury assessment.

Any simple assessment of oil spills should recognize that the greatest risk will be to life on the surface of the water, especially animals with fur or feathers that protect them from the cold waters of a sub-Arctic environment. Since oil spilled near a coast almost always comes ashore, shorelines will be oiled, and it will persist, especially on protected beaches or in protected parts of high-energy beaches, so these environments will also be greatly affected.

We also know that floating oil will follow the prevailing winds and currents. So if we had known the tanker route, prevailing winds and currents, organisms and environments that were most vulnerable, there would have been good up-to-date information on the populations of the organisms at risk. Instead, there was virtually no usable information on the status of the intertidal and subtidal communities in Prince William Sound. The last good census of sea otters in Prince William Sound, creatures which die from hypothermia when only 30% of their pelts are oiled, was carried out in 1984. And the last good censuses of murre colonies, the seabirds that are well known to be extremely vulnerable to oil spills, was carried out in the 1970s. I don't intend to belabor our lack of preparation for injury assessment, but will instead attempt to point out some of the consequences of not having the information. I will also indicate some of the other practical limitations to precise injury assessment.

The Natural Resource Damage Assessment studies produced results of less certainty because good up-to-date population data was not available. Consequently, additional studies were done in an effort to provide more certainty. In other words, techniques and approaches were often not closely linked to precise estimates of population level impact. This, of course, increased the costs of the Natural Resource Damage Assessment studies. Under these conditions the ultimate legal declarations or findings on injured resources become more dependent upon policy decisions regarding how uncertain results would be interpreted.

Let us start our inquiry into certainty by considering the different types of information that were gathered after the spill. These were: population counts, counts of carcasses, mortality rates of eggs and larvae, and sublethal effects...
(e.g., biochemical alterations, histopathological alterations, reduced growth). Also, the presence of oil in the immediate environment of an organism or in the tissues of organisms documented exposure, the usual prerequisite for further conclusions regarding injury. This information can be ordered in a hierarchy as to seriousness of the impact and the certainty it provides.

First, let us consider population counts. Because of the great variability in populations from place to place and at different times, scientists aim to have enough pre-impact data in a variety of areas and in enough years to be able to understand how populations change naturally. This then allows a comparison of pre-impact population data to post-impact population data in both affected and non-affected areas. Generally, in order to conclude that there was an impact, the change observed in the impacted population must be larger than expected by chance compared to past fluctuations or larger than can be observed at the same time in the non-impacted population. There are statistical tests designed to test rigorously for an impact using this type of data.

Given the lack of good up-to-date baseline data on many populations, how does one assess the effect of the spill? The next best approach is usually to compare populations in oiled and unoiled areas after the spill, and this was done for most populations that were studied. This is where large amounts of uncertainty can enter into an assessment of spill impacts. It is very difficult to separate changes due to natural geographic and temporal variability from changes due to impact unless the resources are studied for many years after it can reasonably be assumed that the impact has ceased. The confounding effects of natural variability can, however, be mitigated by replicating sites, so that several oiled areas and several unoiled areas can be matched and compared. This was done for the intertidal and subtidal studies in order to identify impacts. Still, with this approach it is possible that factors unaccounted for in the design, such as natural differences in currents, may be having systematic effects across replicate treatments.

Second, let us consider recovered carcasses. Carcass counts, usually derived from animals found on beaches, can be used to model total mortality by estimating the rates of ingestion after death, rates of scavenging, burial in beaches, and the number and frequency with which beaches are searched. This was done for birds, and to some extent for sea otters. Using such modeling techniques it was estimated that the 36 thousand birds that were recovered, mainly from beaches, represented about 400 thousand total bird deaths. Carcass information will often provide the only unequivocal evidence of the impact of the spill, if mortalities are absent or if damages are within the natural variability of the population. This was the case with many species of birds, such as Bald Eagles.

Third, let us consider the role of information about elevated mortality of eggs and larvae. This applies particularly to animals or plants that produce large numbers of eggs, of which only a few percent survive, as is the case for most fish. So, for example, the spill appears to have caused an increased egg mortality in pink salmon in Prince William Sound every year since the spill, and egg and larval mortality in herring in 1989. The real biological significance of the loss of 5 to 20% of the eggs of fish that typically spawn thousands of eggs, of which on average less
than a few percent survive naturally, is a major unanswered question for environmental scientists. We put programs in place for both these species to estimate effects on adults, but no effects were detected. One could argue that this really could have been large effects due to the spill on wild stocks of adult pink salmon (the accumulated effects of increased mortality of eggs and retarded fry growth), and they were undetected because of the large variability in the counts of returning salmon. One could also argue that a change in rate of mortality in egg and juvenile stages is not going to make much of a difference in a natural mortality rate of greater than 90%. The restoration programs for pink salmon, for which we have no data that directly indicates an effect on the adult population, could amount to tens of millions of dollars. Several millions of dollars have already been spent on assessing damages to pink salmon in comprehensive programs in 1989 and 1990. The cost of herring programs for damage assessment exceeded one million dollars, but there is less that appears to be feasible for restoration of herring short of limitation of the adult harvest. These cases contrast with studies of Dolly Varden where clearly documented differences in survival of adults between oiled and unoiled streams provide a better basis for claiming injury to the population, but do not prove it without comparable natality rates.

Fourth, let us consider the role of sublethal effects. Documentation of sublethal effects of the spill may serve two general functions in an injury assessment. First, it may indicate that the exposure to oil resulted in some negative effect to the organism. Second, if the negative effect was debilitating enough it may imply decreased survival that could, in turn, eventually affect the population. If a census is taken and there is considerable uncertainty that an organism has been impacted, the documentation of sublethal effects will increase the certainty. This was the case with herring, where the main impact observed was the production of deformed larvae. Conversely, if there is some doubt whether natural variability is confounding oiling effects, the lack of substantial sublethal effects suggests oil may not be the cause. These sorts of interpretations must be made cautiously, as we know very little about the toxicology of oil in the species that were studied, and most sublethal effects may have causes other than oil. For example, in Dolly Varden there are clear differences in rates of return of individuals using streams in oiled versus unoiled areas in 1989-1990 and in 1990-1991, which is strong evidence of differences in mortality rates in the populations. There were high concentrations of oil metabolites in the bile of Dolly Varden in 1989, but the concentrations decreased dramatically in 1990 without a concomitant increase in survival rate. In addition, examination of tissues of anadromous Dolly Varden revealed no differences in histopathological alterations that could be attributed to oil. It may mean that Dolly Varden are not susceptible to histopathological alterations from oil exposure, as some fish species are more resistant than others, but the outcome of these analyses does raise uncertainties about the injury.

Now let us consider how this information can all fit together. We assume that it is the population-level impact (on adults) that is of ultimate interest for injury assessment and it is the unrecovered population that deserves our highest consideration in restoration.
To return to the concept of a hierarchy of evidence, the strongest data on injury is a large number of oiled carcasses with many prime-aged animals, especially if the modeling indicates that a significant proportion of the population was killed.

Next, evidence is almost as strong if the contrast of populations after the spill shows that there was a decrease after the spill in the oiled environment that did not occur in the unoiled environment and that the decrease was probably not due to natural fluctuations (based on sufficient prespill information). This kind of evidence is bolstered with any of the following ancillary information: dead oiled organisms, evidence of high oil exposure, sublethal effects on survivors, or increased mortality to eggs and larvae. One case that came close to fitting this model was harbor seals, where there was a good record of the population annually through 1988 in Prince William Sound. A weaker form of this type of evidence exists where prespill population data were limited in extent or had been collected long enough before the spill occurred that natural fluctuations in populations could enter into the interpretation. This was common for bird and mammal populations where major data collection efforts were made in the 1970’s and, in some cases, again in the middle 1980’s to document populations that were subsequently affected by the spill (e.g., sea otters, murres, eagles, and many other species of birds).

Next, in cases where a population decline is based only on post-spill data which can not be contrasted with prespill information, evidence of spill impact is less certain. The degree of certainty can be maximized if multiple unoiled and multiple oiled sites are contrasted. As mentioned earlier, these sorts of comparisons, without the benefit of good pre-spill information, were commonly made in the Exxon Valdez spill injury assessment (e.g., subtidal and intertidal communities). Careful planning of sampling sites needs to be carried out to minimize the confounding of natural differences and oil-induced differences. Also, the interpretation of differences should carefully consider the possible role of natural variability in producing the observed results. Documentation of differences in exposure, vital biological rates (including reproduction), and sublethal effects can further clarify the certainty as to whether the observed differences in post-spill populations are due to natural causes or to oil exposure.

For those of you at the symposium interested in pursuing the concept of uncertainty in injury assessment, I suggest you listen carefully to the presentations to see how the investigators deal with imperfect knowledge of injury and how oil impact and natural changes are discussed. One of the imperatives of objective science is to discuss alternative interpretations. Studies with imperfect data in which the possible role of natural causes of change are not discussed should be viewed with skepticism.

Since the consequences of being unprepared seem to be greater costs and greater uncertainty about injured resources, their recovery and need for restoration, what should we be doing now in order to be better prepared to assess damages resulting from the next oil spill? The answers seem clear in retrospect—ongoing monitoring programs collecting data on intertidal and subtidal zones; annual counts of sea otters, eagles, murres and other sea birds; and gathering more experimental information on oil toxicology of common species. A basic and rela-
tively inexpensive monitoring program carried out over many years might tell us enough so that if another spill were to occur along an Alaskan tanker route we might get better injury information at lower cost. In the process we would also learn more about the natural resources we are trying to protect.
Fate of the Oil Spilled from the T/V Exxon Valdez in Prince William Sound, Alaska

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This paper integrates field observations from several different investigations, along with published experimental and field data on spilled oil in the marine environment, in an effort to reconstruct the overall fate of the 10.8 million gallons of oil spilled from the Exxon Valdez through the fall of 1992. During the first 6 weeks after the spill, the location and movements of the floating oil were tracked visually by observers from aircraft and on the shoreline. For this period, the distribution of floating and beached oil was hindcast by NOAA's Oil Spill Simulation Model (Galt et al. 1991), which took into account real-time data for the wind fields and currents moving the slick. A weathering model based on extensive experimental data (Payne et al. 1991) was used to estimate initial losses due to evaporation and related weathering processes. By the end of April, 1989, approximately 20\% of the spilled oil had evaporated, and approximately 20-25\% had been dispersed naturally into the water column. About 25\% of the oil had been carried out of Prince William Sound as floating or dispersed oil, and most of the remainder (approximately 40-45\%) had beached within the Sound. No quantitative measurements were made of volatile constituents in the atmosphere, and the oil evaporation rates were estimated from volatility models based on theoretical data under the temperature and wind conditions prevailing at spill time. The accuracy of theoretical evaporation rates was confirmed through compositional analyses of floating oil. During the first 3 days of the spill, before its initial landfalls, the most volatile constituents (accounting for approximately 13\% of the spill volume and including most of the benzene, toluene, and alkanes through C\textsubscript{14}) evaporated (Payne et al. 1991). The atmospheric trajectory for these initially evaporated materials from the still concentrated slick passed over Naked Island and Eleanor Island (Hanna et al. 1991). Measurement of the oil dissolved and/or dispersed in the water column was initiated 6 days after the spill. Concentrations of volatile, monoaromatic hydrocarbons in seawater were often in the 1-5 ppb range in close proximity to floating or beached oil during early April, but had generally declined to concentrations near or below analytical detection limits (about 0.18 ppb) by the end of April (Neff 1991). During the first 2 weeks of April, concentrations of total polynuclear aromatic hydrocarbons (PAH) in the water column were frequently also in the range of 1-7 ppb, especially near heavily oiled beaches (Neff 1991; Payne et al. 1991; Short &
Rounds 1993a). Aqueous PAH concentrations were generally below 1 ppb by May 1, and below 0.1 ppb after July 1. In some locations, however, elevated petroleum hydrocarbon concentrations were measured in transplanted filter-feeding mussels into 1991, indicating the persistence of extremely low concentrations of dissolved and particulate oil components in the water column through that time (Short & Rounds 1993b).

The oil recovered by skimming operations in 1989 accounted for about 8.5% of the original spill volume. Cleanup operations on the beaches during the first four summers led to the recovery and disposal of approximately 31,000 tons of solid oily wastes (Carpenter et al. 1991; ADEC 1992), which were estimated to account for 5 to 8% of the original spill volume. Annual beach surveys conducted in the fall and spring indicated that about 90% of the oil in surface (<25 cm) beach sediments was removed by natural processes (storm erosion and biodegradation) during winter 89-90, whereas only about 40% of the deeper oil was removed (Michel et al. 1991, Michel & Hayes 1992). By 1992, the combination of natural processes and cleanup activities had eliminated nearly all of the surface oil, though small amounts persisted along many shoreline segments in the Sound. Reworking by storms and berm relocation had removed nearly all the oil from the upper intertidal zone. In a few areas appreciable quantities of oil remained trapped under the central platforms of exposed cobble/boulder beaches, where it had penetrated deep into the substrate. The oil trapped in such protective crevices may be only moderately weathered, unlike oil deposited onto coarse sand or fine sediments, which by 1992 was generally highly weathered (Roberts et al. 1993). Relatively unweathered oil also persisted in 1992 in the sediments and byssal mats underlying some low gradient mussel beds in Prince William Sound (Babcock et al. 1993). Coincident with the decline of oil on the beaches, concentrations of oil (O’Clair et al. 1993) and numbers and activity of hydrocarbon-degrading microbes (Braddock et al. 1993) increased in subtidal sediments in 1990. At heavily oiled locations (e.g., Northwest Bay on Eleanor Island, Herring Bay on Knight Island, and Sleepy Bay on Latouche Island), peak subtidal concentrations occurred between September 1989 and September 1990 at depths between 3 and 20 m. Corresponding decreases were not always noted in oil concentrations at mean lower low water (0 m). Near some heavily oiled areas, low concentrations of residual petroleum hydrocarbons and associated concentrations of microbial hydrocarbon-degradation also were detectable during the summer of 1990 in deeper (40-100 m) subtidal sediments where no activity had been detected in 1989. Measures of microbial hydrocarbon degradation had declined in 1991 at all sites and depths. Sediment traps deployed at 10-20 m depths in these areas indicated that oil was sorbed onto suspended particulate material (Sale et al. 1993), reflecting transport of oiled sediments from the intertidal zone into deeper waters, at least through the winters of 1989-90 and 1990-91.

Much of the floating mousse that departed Prince William Sound was deposited on shorelines in the Kenai and Kodiak areas. Galt et al. (1991) estimated that about 2% of the spilled oil floated past Cape Douglas into the Shelikof Strait where heavy mousse was deposited between Hallo Bay and Wide Bay during
April 29-May 2, 1989. Because of the extent of prior weathering and emulsification, this stranded mousse did not penetrate into shorelines nearly to the extent that the fresh oil did in Prince William Sound, and as a result, was much more amenable to physical removal. In the areas of heaviest shoreline oiling along the coasts of the Kenai and Alaska peninsulas, extensive cleanup activities were carried out during June-July 1989, and by early August, most of the beaches appeared generally clean with only sparsely distributed small tarballs and mousse patties. On sandy beaches some mousse was buried by shifting sands (Dewhurst 1993a). In fall 1989, after initial cleanup operations, a total of 9.7 km of shoreline along the Kenai coast was characterized as heavily oiled and 12.9 km as moderately oiled. Of this total, 4.35 km and 1.0 km were still described as moderately oiled in fall 1990 and spring 1991, respectively (ADEC 1992). By summer 1990, the most commonly observed form of oil along the coast of the Becharof Refuge on the Alaska Peninsula was staining on shoreline debris (Dewhurst 1993b).

Estimates will be provided for the distribution of the spilled oil in different environmental compartments from the start of the spill through the fall of 1992, and the chemical evolution, or weathering, of the oil during that time. Evaporation was a dominant process during the first few days. Relatively unweathered oil stranded along shorelines in Prince William Sound, where it penetrated into beach gravel. The oil that exited the Sound was more highly weathered and generally did not penetrate deeply into the substrate when grounded. Most of the oil beached in the Sound has been removed through a combination of biodegradation, natural erosion and cleanup activities, but relatively unweathered oil still remained in 1992 in isolated and protected situations in the sediments of some Prince William Sound beaches. The overall behavior of the spilled oil from the Exxon Valdez was generally consistent with prior understanding of the behavior and fate of oil in the marine environment, and the observations and measurements recorded after this spill provided useful validation for existing models of oil transport and weathering.

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The Exxon Valdez Cleanup—The First Six Months
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Vice Admiral Robbins was the Federal On Scene Coordinator for the Exxon Valdez oil spill from April 16 until September 30, 1989. It was during this period that the Exxon Company undertook this country’s largest oil spill cleanup. With over 12,000 personnel involved, it was described by some as rivaling the Normandy invasion.

From the moment of the grounding of the Exxon Valdez, it was inevitable that a great proportion of the 260,000 barrels of North Slope crude would find its way onto the pristine shores of Alaska, causing changes to the lives and livelihoods of thousands. Alaskans who had never worked outside of the home found themselves working along the shorelines, attempting to minimize the impact of such a spill. Fishing, hunting and recreation came to a standstill for the summer of 1989. Fishing boats were pressed into service as support vessels for the monumental task. New buildings were built in Valdez and other towns and villages; telephone services were increased many fold; millions of dollars worth of equipment was imported; communities swelled to many times their original size; barges, boats, cranes, and house trailers grew like topsy. No effort was spared.

Despite all this, cleanup was slow and marginally effective. Oil on any shoreline is tough to remove, but Alaska’s presented new challenges. New methods and equipment were aggressively tested—many were found wanting, while others were breakthroughs. The mechanics of the cleanup operation were only a portion of the problems faced by the Federal On Scene Coordinator.

Complicating the cleanup process were problems which made decision-making difficult. Everyone, it seemed, had an interest in the operation. Some of those interests were based on a true concern for the environment, while others appeared to have a hidden agenda. Faced with an operation which dwarfed any past effort, every action by the participants was magnified under the microscopic eye of the news media. Little escaped the watchful eye of the hundreds of agencies, departments, civil organizations, environmental groups, and others who had an interest. One official described it as a frustrating effort to keep “all the kittens in their box”.

The national document which organizes the efforts to prevent and to clean up oil spills, the National Contingency Plan, by its very nature, is a consensus document. To win agreement on its content, compromises were necessary. As an example, the Federal On Scene Coordinator is just that: a coordinator without real authority. The State On Scene Coordinator is in the same position. If federal interests differed with Alaska’s, conflict often ensued. To counter some of the conflict, committees were formed to provide advice to the Federal On Scene Coordinator. These provided a high level of interest group input into decision-making and were quite successful.

The weakness in the National Contingency Plan did not greatly hamper the cleanup operation—it only complicated
the process. There were exceptions, however. An example was the refuse issue. Very early in the cleanup it was apparent that a means of getting rid of refuse was going to be needed. With tons and tons of trash being generated each day, local facilities in Valdez and other small towns were not going to be adequate. In a joint meeting on the issue it was decided to incinerate the oil-tainted debris. Exxon immediately contracted for incinerators to be constructed and barged to Alaska. At that point the Federal On Scene Coordinator lost control. Public resistance to incineration grew despite some pretty convincing scientific information which indicated that no one was going to be endangered by the process.

The conflict raged throughout the summer with the final result that one of the two incinerators was used, but for less than a fortnight. Most of the refuse was hauled to Oregon for disposal in a very expensive landfill reserved for hazardous materials. More than $5 million was wasted on this project.

Another problem was generated by the concern of Alaskans who feared that Exxon would leave the mess at the end of the summer, never to return. The state therefore wanted to ensure that every shoreline was completely free of oil before the work parties moved on. With the general agreement that work would have to terminate at the latest on 15 September in order to avoid the dangers of winter, complete cleanup was an impossible task.

The Federal On Scene Coordinator set as the major goal for the summer of '89 to render the polluted shoreline relatively neutral so the oil wouldn’t spread during the winter months, causing more damage. Tensions ensued between the Federal On Scene Coordinator and the State representatives over such matters as “how clean is clean” and when to move on to the next shoreline. Eventually a compromise was reached. It was agreed to use the word “treated” rather than “cleaned”.

These are two examples of the problems which arose during the cleanup operations, but there were successes. Through Exxon’s worldwide organization, equipment was made available the likes of which had never been seen before. Skimmers, water heaters, fertilizers and techniques were brought to bear effectively without concern for the cost involved. It was found for instance, that the French had some of the best skimmers available. Those skimmers dotted the shoreline as the summer passed.

It was found that the French had developed a fertilizer which was ideal for bioremediation applications. Tested by a joint program with the U.S. Environmental Protection Agency and Exxon, it was found that there were microbes existing along the shorelines in Alaska which could help in the cleanup with little negative impact on the environment. These critters only had to be encouraged with some nutrients and the French fertilizer was the best available.

Unfortunately 450 tons were needed and only some 250 tons were available. The French factory which made it was to be shut down for August vacations. Exxon used their considerable resources to induce the plant to stay open until the full 450 tons were made.

The application of that fertilizer to the shorelines to enhance the growth of indigenous microbes which consume the oil was one of the great successes. Shorelines that were black with residual oil after “treatment,” were greatly improved after application of the fertilizer.
Plenary Session: The Exxon Valdez Cleanup

There were other successes. While fishing came to a standstill during that infamous summer of '89, the salmon were largely unscathed. Hatcheries were protected and later years' runs were very healthy. Shorelines which experts said would take decades to recover, seem to have largely recovered in under four years. Only time will tell what the long term impact of the Exxon Valdez spill will be, but there is optimism.

At the end of the summer, those who were there could honestly say that they gave it "their best shot". Perhaps we'll never know whether the long hours of dedication of those thousands of people significantly helped save the environment, but if they didn't, it wasn't for the lack of trying. One lesson came through to everyone—spilling oil has to stop!
Cultural Resources and the Exxon Valdez Oil Spill
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The state of knowledge about human history in the Northern Gulf of Alaska at the time of the Exxon Valdez oil spill was fragmentary at best. Except for excavations at a single site, no substantive archaeological work had been done in Prince William Sound since the 1930's. No serious large scale inventory or testing had ever been done on the Outer Coast of the Kenai Peninsula. Kodiak Island and the Alaska Peninsula were the only areas known archaeologically and data came from a small number of sites. In the face of impending danger to sites, resource managers in the spill area were forced into the awkward position of protecting known sites while at the same time scrambling to identify undocumented sites.

Archaeologists were alarmed about potential injuries to sites in the spill area because many sites had subsided into the intertidal zone during the 1964 earthquake. Those sites would be located in the path of the spreading oil slick. The primary concern was the effect of crude oil and cleanup procedures on the sites. Coupled with that was the concern that undocumented sites could unknowingly be impacted during cleanup. The unexplored status of the area made the problem particularly disturbing.

The charge of protecting cultural resources during the spill and subsequent cleanup came from several authorities. Federal mandates included the Archaeological Resources Protection Act (ARPA) and the National Historic Preservation Act of 1966 (NHPA). The ARPA directed land managing federal agencies to protect cultural sites on land they managed. The NHPA directs federal agencies "undertaking actions" such as spill cleanup, to consider the effects on cultural resources. The Alaska Historic Preservation Act protects sites on state land, including the intertidal zone.

Close coordination between the Alaska State Historic Preservation Office (SHPO), the U.S. Coast Guard On-Scene Coordinator, native representatives, federal representatives and the Exxon Cultural Resource Program protected cultural resources during cleanup. Coordination occurred during cleanup planning by Exxon and a representative of the SHPO reviewing Exxon archaeologist's reports for adequacy and planned activities. Proposed cleanup methods and scope were altered prior to initiation to reduce danger to known sites. Federal and native representatives reviewed and discussed actions during Shoreline Committee meetings. Agency and native corporation archaeologists monitored cleanup activities on a sporadic basis.

Agency concerns about the effect of crude oil contamination on the radiocarbon dating process prompted a laboratory study of those effects. The contractor concluded that significant effect would occur but that sample cleaning partially reduced the error. Testing that conclusion on specific sites was the next step of injury assessment. Unfortunately, the radiocarbon study did not get funded until 18 months after the spill and follow-
up studies were delayed another year.

Due to delays, field damage assessment studies did not take place until 1991. Damage assessment studies were requested during 1989 by the panel of archaeologists advising the Trustees staff. In 1990 the C-14 laboratory study was funded. The state and federal agencies provided funds during 1991 and the State University of New York, Binghamton, began fieldwork at the end of the 1991 season. The scope of the 1991 project was reduced when Trustee representatives decreased available funding. The project aimed at testing a series of sites for injury, surveying to check the adequacy of the Exxon surveys, checking several soil chemicals for alteration by oiling, and testing a model developed to predict site locations. Radiocarbon dating tested sites was a basic part of the project.

Delays in awarding a damage assessment contract during 1990 and 1991 prompted the state to begin a much smaller and tightly focused study in May 1991. The state study followed up on the conclusions of the earlier radiocarbon study by checking selected sites. Alternate methods of dating archaeological remains were contrasted with radiocarbon estimates to check for injuries from oil contamination. The study was designed to compliment the larger multi-agency study.

Another approach to assessing injuries to archaeological sites by spill related activities was a compilation of information in agency and Exxon documentation. Field notes from various parties, monitoring reports, and SCAT reports were examined to determine kinds and degree of impacts. This method of investigation was used partly because of the need for a more timely idea of impacts and partly to assess the adequacy of the documentation process. Although results of the document study provided only a rough idea of injuries, it was very useful in estimating injuries resulting from cleanup and attendant vandalism. Valuable insights were gained in the types and detail of documentation needed from site identification surveys and monitoring. The study also provided the core data base for assessing damage to the area sites.

Assessment of monetary values for restitution followed the documents study. Findings of the state and multi-agency funded studies also provided data useful in determining levels of damage. A method of assessing damage based on ARPA procedures was used to give a monetary estimate. The method has been repeatedly used in other cases and provided very conservative cost estimates. The most clearly injured sites were assessed for damages while the less adequately documented sites were deleted from the process. Sites considered had sustained damage from cleanup related activities rather than from oiling.

Several useful conclusions about archaeology and the oil spill are possible based on damage assessment studies. The most important conclusion was that the sites generally were not directly effected by the spill. The most extensive damage resulted from vandalism because of more people having widespread knowledge about area sites. That knowledge expanded due to increased population and activity levels during the cleanup. Another source of impact was directly from cleanup activities. Impact from cleanup was slight because of cleanup workplan review and clean-up technique alteration with archaeology in mind. The Exxon Cultural Resource Program/agency cooperation was effective
in keeping cleanup impacts minimal.

Lack of field assessment studies for the first two years after the spill caused inefficient resource management. Information collected by archaeologists and other monitors early in the cleanup phase could have included the data needed to protect the resource. Future considerations identified from the experience of the Exxon Valdez oil spill are the need for a credible basic inventory, a response plan, and improved monitoring. Inventory and planning are long term projects which are typically difficult to fund. Improved monitoring will require analysis of existing studies and listing the information required during future emergencies.
Subsistence
James A. Fall
Alaska Department of Fish and Game

This plenary session presentation provides information about changes in subsistence uses of fish and wildlife resources in 15 Alaska Native communities whose hunting, fishing, and gathering areas were affected by the Exxon Valdez Oil Spill. It also reviews the work of the Oil Spill Health Task Force, a group of agencies and organizations which formed to address questions concerning the safety of using subsistence foods harvested from the oil spill area.

Before 1989, the Division of Subsistence of the Alaska Department of Fish and Game conducted baseline research in the 15 communities. These are Tatitlek and Chenega Bay in Prince William Sound; English Bay (Nanwalek) and Port Graham in lower Cook Inlet; Akhiok, Karluk, Larsen Bay, Old Harbor, Ouzinkie, and Port Lions in the Kodiak Island Borough; and Chignik, Chignik Lagoon, Chignik Lake, Perryville, and Ivanof Bay on the Alaska Peninsula. In 1990, the population of these 15 communities was 2,036, 82.3 percent of which was Alaska Native.

These studies documented large and diverse subsistence harvests in the 1980s, ranging from about 200 pounds per person to over 600 pounds per person usable weight per year. These are substantial harvests, given that the average American family purchases about 222 pounds per person of meat, fish, and poultry annually. These subsistence harvests contained a wide variety of resources, including salmon and other fish, marine invertebrates, land mammals, marine mammals, birds and eggs, and wild plants. Virtually every household in all 15 villages used and harvested wild foods, which were widely shared within and between communities. A patterned seasonal round of subsistence harvesting structured much of economic, social, and cultural activities in each community.

In early 1990, Division of Subsistence researchers interviewed representatives of 403 households in these 15 communities. Study findings revealed that after the spill, subsistence harvests declined greatly in the 10 communities of Prince William Sound, lower Cook Inlet, and the Kodiak Island Borough compared to pre-spill averages. Annual per capita harvests in Chenega Bay and Tatitlek were down 57 percent. In these villages, the range of resources used also dropped in the 12 months after the spill. While the average household in Tatitlek used 22.6 kinds of wild foods from April 1988 through March 1989, in the next year, this average was only 11.6 types. The change at Chenega Bay was much like that of Tatitlek. In a 12 month study year in 1985-86, the average household at Chenega Bay used 19 kinds of wild foods, compared to just 8.2 kinds in the year after the spill. Similar changes were documented for English Bay and Port Graham. Also, subsistence harvests in all six Kodiak area villages declined in 1989 compared to pre-spill averages, although a wider range of changes was documented. In contrast, subsistence harvests in the five Alaska Peninsula com-
Communities showed little change, or increased, in 1989 compared to 1984, the only pre-spill year for which comprehensive data are available.

When asked to provide reasons for these declines, 33.2 percent of the sampled households attributed reductions in overall subsistence harvests to concerns about resource contamination, and 44 percent said such a concern had caused a reduction in their harvest of at least one kind of subsistence food. Levels of concern about contamination were notably higher among Prince William Sound (92.1 percent) and Lower Cook Inlet (77.8 percent) households than in the Kodiak area (29.5 percent) or Alaska Peninsula (22.8 percent) communities. Other reasons cited for lowered levels of subsistence uses included the time harvesters spent on the oil spill cleanup and the perception that less resources were available because of spill-induced mortalities.

As noted above, the primary response to the issue of subsistence foods contamination was directed by the Oil Spill Health Task Force. The Task Force included the Indian Health Service; the Alaska departments of Fish and Game, Health and Social Services, and Environmental Conservation; the National Oceanic and Atmospheric Administration; Exxon; and two regional Alaska Native service organizations, the North Pacific Rim (now known as Chugachmiut) and the Kodiak Area Native Association. The task force coordinated and reviewed research on subsistence food safety, developed a consensus on health issues, and communicated findings of the studies to the communities through health bulletins, newsletters, public meetings, and a video.

As part of this effort, 309 samples of fish and 1,080 samples of shellfish that had been collected from 146 traditional harvest areas near the 15 communities over a three year period were tested for signs of oil contamination. For the most part, the samples were collected with the assistance of residents of the communities at sites recommended by community leaders. The tests were conducted at the National Marine Fisheries Services' Northwest Fisheries Center in Seattle. These highly sensitive tests measure the concentrations of polycyclic aromatic hydrocarbons (PAHs) in edible tissues. The findings were reviewed by a panel of toxicologists who provided a health assessment.

Evidence of exposure to oil was found in some of the samples of fish, but none of the samples had PAH concentrations so high as to be a human health concern, according to the group of toxicologists. The majority of shellfish from most sites also were determined to be safe to eat. However, even in 1991, PAH concentrations remained elevated in shellfish samples from Windy Bay, a highly oiled site on the lower Kenai Peninsula. Therefore, the advice of the Task Force has remained cautious; fish from the oil spill area are safe to eat, but people should still avoid using marine invertebrates from beaches with obvious oiling.

As part of the Oil Spill Health Task Force program, samples of ducks, deer, and marine mammals were also tested. Evidence of exposure to oil was found in some of the duck and deer samples, but PAH concentrations were well below those considered dangerous by the health experts. The blubber from oiled seals taken in Prince William Sound soon after the spill had elevated PAH concentrations. Seals taken in the same areas a year later, which no longer showed obvious signs of oiling, showed reduced concentrations of PAHs in their blubber, al-
though these concentrations were still higher than samples from seals from uncoiled areas. Members of the Task Force advised that these elevated concentrations of PAHs in ducks, deer, and marine mammals were still well below those considered to be of concern for subsistence users.

In 1991, the Division of Subsistence conducted follow-up interviews with 221 households in seven spill-area villages pertaining to subsistence harvests during the second post-spill year. Harvest levels increased at Port Graham, Larsen Bay, and Karluk, and matched at least one pre-spill measurement. The range of resources used was also up substantially in all three communities. In two other communities, Ouzinkie and English Bay, harvest levels also increased, but remained below pre-spill averages. This general increase in harvest levels and range of wild foods used suggests some renewed confidence in using subsistence foods during 1990. On the other hand, lingering concerns about food safety were expressed in all five villages. Some families reported that they had resumed their subsistence harvests despite misgivings because they could not afford to purchase substitutes and could no longer do without culturally important foods.

In contrast, no evidence of a recovery in subsistence uses in the second post-spill year was found for Chenega Bay and Tatitlek. At Chenega Bay, subsistence harvests from April 1990 through March 1991 were 139.2 pounds per person, virtually the same as the previous year (148.1 pounds per person) and still well below the pre-spill average of 340 pounds per person. At Tatitlek, the 1990-91 per capita harvest was 152.0 pounds, compared to 214.8 pounds per person in the first post-spill year and a pre-spill average of 497.6 pounds per person. In these Prince William Sound communities, deep concerns about the safety of using subsistence foods from their traditional harvest areas continued.

In addition, respondents from Chenega Bay and Tatitlek reported perceived declines in the numbers of some important subsistence resources, such as certain species of waterfowl, marine invertebrates, and marine mammals, which led to well below normal subsistence harvests in 1990-1991.

Preliminary information collected by the Division of Subsistence during another round of systematic surveys suggests that subsistence harvest levels in the Prince William Sound communities increased in the third year after the spill. However, subsistence harvests of waterfowl, marine invertebrates, and marine mammals continue to be abnormally low. Also, despite increased harvests and uses, concerns persist about the long-term health risks associated with using subsistence foods.
Overview of Intertidal Processes, Damages and Recovery
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The intertidal zone occupies the unique triple interface among the lithosphere, hydrosphere, and atmosphere. The land provides the substrate for occupation by intertidal organisms, the water the vehicle to supply necessary nutrients and to transport propagules (newly colonizing organisms), and the air a medium for passage of solar energy and also a source of physiological stresses. The intertidal zone is exceptionally biologically active and productive. Wind and tidal energy combine to supply the intertidal zone with planktonic foods produced in the productive photic zone (uppermost layer of water where photosynthesis occurs) of the coastal ocean. Runoff from the adjacent land mass injects new supplies of inorganic nutrients to fuel high coastal primary production of plants. The consequent abundance and diversity of life and life forms in the intertidal zone serves many consumers, coming from land, sea, and air, and including humans. The intertidal ecosystem simultaneously provides intrinsic aesthetic and cultural appeal in an environment undeniably shaped by forces outside the control of mankind.

The same physical transport processes that are responsible for its high level of biological production also place the intertidal zone at great risk to floating pollutants, such as oil. Oil floats on the surface of the water, is transported there by winds and currents, and, if spilled near the coast, is likely to be deposited on shore. There it encounters intertidal organisms and adheres to intertidal substrata, where it remains until chemical transformation and physical transport remove it. Thus, the intertidal zone becomes a natural focal point for the study of damages to natural resources following a coastal oil spill.

The biota of intertidal habitats varies with changes in physical substrate type, wave energy regime, and atmospheric climate. Substra a range from immobile rocks, to boulders and cobbles, to sands, and finally to muds at the finest end of the size spectrum. Rock surfaces in the intertidal zone tend to be populated by epibiota (surface dwelling organisms), attached macro- and microalgae, sessile suspension-feeding invertebrates, and mobile grazing invertebrates. Unconsolidated ("soft") substrata, the sands and muds, are occupied by large plants in low wave energy areas, and microalgae and infaunal (buried) invertebrates in all energy regimes. Mobile scavenging and predatory invertebrates occur on both high and low energy shorelines. Intertidal communities vary with wave energy because of biomechanical constraints (especially on potentially significant predators), changing levels of food supply, and interdependencies between wave energy and substratum type. Intertidal communities tend to be more luxurious in temperate climates, whereas freezing and ice scour limit intertidal biota in polar regions and desiccation and effects of intense solar radiation may limit intertidal biota in the tropics. The rocky intertidal communities of the Pacific Northwest may be the richest on earth.
The rocky intertidal ecosystem probably represents the best understood natural community of plants and animals anywhere. Ecologists realized over 30 years ago that this system was uniquely well suited to experimentation because the habitat was accessible and the organisms moveable and manipulable.

Consequently, ecological science has produced a detailed understanding of the complex of processes involved in determining patterns of distribution and abundance of rocky intertidal organisms. Plants and animals of temperate rocky shores exhibit strong patterns of vertical zonation in the intertidal zone. Physical stresses tend to limit the upper distributions of species populations and to be most important high on shore, whereas competition for space and predation tend to limit distributions lower on the shore. Surface space for attachment is potentially limiting to both plants and animals in the rocky intertidal zone. In the absence of disturbance, space becomes limiting and competition for that limited resource results in competitive exclusion of inferior competitors and monopolization of space by competitive dominant species.

Physical and biological disturbance and recruitment limitation are all processes that can serve to maintain population densities below the level at which competitive exclusion occurs. Because of the importance of such strong biological interactions in determining community structure and dynamics in this system, changes in abundance of certain species can produce intense direct and indirect effects that cascade through the ecosystem.

Intertidal communities are open to use by consumers from other systems: the great extent and importance of this habitat as a feeding grounds for major marine, terrestrial, and aerial predators render the intertidal system a key to integrating the health and recovery of the entire natural ecosystem. The intertidal resources of Prince William Sound and adjacent areas affected by the Exxon Valdez oil spill, for example, are critically important feeding grounds for many marine consumers (sea otters, Dungeness and other crabs, juvenile shrimps, rockfish, cod and juvenile fishes of other exploited species), terrestrial consumers (bears, river otters, and people), and avian consumers (black oystercatchers, harlequin and other ducks, and numerous shorebirds). Thus, the intertidal habitat provides vital ecosystem services in the form of prey resources for all coastal habitats, as well as human services in the form of commercial, recreational, and subsistence harvest of shellfishes and aesthetic, cultural, and recreational opportunities. The intense focus on the intertidal habitat following Exxon Valdez oil spill was well justified.

Rapidly following the spill, oil became deposited along hundreds of miles of intertidal habitat in Prince William Sound, the Kenai Peninsula, lower Cook Inlet, the Alaskan Peninsula, Kodiak Island and beyond. A massive cleanup process was mobilized with the intent of displacing the oil from the intertidal zone where it was so evident to even casual observers and where its mere presence degraded recreational and cultural values of wilderness shorelines. Cleanup techniques were diverse and not chosen to minimize damages or maximize recovery rates of intertidal organisms. In fact, evidence from subsequent biological studies suggests that the widely applied pressurized hot water treatment was more damaging than the oil to inter-
tidal ecosystems and retarded recovery. The cleanup efforts did serve to remove much of the deposited oil from the intertidal habitat and to displace it out of sight into the subtidal environment. Only very small areas of salt marsh habitat were oiled, where previous studies have shown natural cleanup of the low-energy, anoxic muds to take exceptionally long times. Winter storms accelerated the removal of oil from heavily oiled beaches, with higher rates of cleaning at more exposed beaches.

Despite the intense cleanup effort and the natural degradation and physical redistribution of residual hydrocarbons on intertidal beaches, oil in the intertidal zone remains a major problem more than 3 years later. Armored from wave action by surface layers of cobbles and by overlying mussels, large pockets of largely unweathered oil exist in the protected interstices among the rocks of intertidal shorelines in widely scattered areas. This oil is slowly leaking hydrocarbons into the water, where it is maintaining high levels of contamination in the tissues of the closely associated suspension feeders, such as the blue mussels.

Because of the nature of the blue mussel as “the universal prey” for so many consumers (including especially sea otters, river otters, harlequin ducks and black oystercatchers), the likelihood of continued food chain contamination is high. Continuing reproductive problems with each of these species in the oil spill area may be related to this ongoing contamination of a major component of their diet. In addition, much oil remains in the intertidal zone as asphalt pavement relatively high on shore, where it alters the rock surface chemistry, effects local thermal change in the habitat, and persists as a visual blemish to the previously pristine shorelines.

Intertidal suspension-feeding invertebrates represent a group of special importance as monitors of contamination of the marine environment. These organisms filter huge volumes of seawater to collect food and thereby can concentrate biologically available pollutants (metals and organic contaminants), vastly enhancing detection capabilities over what is possible in water analyses. A long-term monitoring of hydrocarbon levels by National Oceanic and Atmospheric Administration staff in Prince William Sound using blue mussels pre-dated the Exxon Valdez spill and provided background information, against which the large increase of hydrocarbon contamination from the 1989 spill is clearly evident. This pollution-monitoring tool has also shown the subsequent decline in hydrocarbon concentrations to background levels in most places except where the contaminated mussel beds persist.

Analysis of several species of clams by the Alaska Department of Fish and Game also revealed the magnitude and extent of contamination of the food chain with hydrocarbons from the spill, using clams as another intertidal suspension feeder with tremendous importance as a prey resource for higher consumers and as a subsistence food. Clams and especially mussels were sampled intensively over broad geographic areas extending beyond Prince William Sound to provide a relatively complete spatio-temporal tableau of the pattern of Exxon Valdez oil spill contamination using a single method of ecological relevance.

The affects of the Exxon Valdez oil spill on the rocky intertidal communities of plants and animals has been studied intensively and extensively by special-
ists at the University of Alaska, NOAA, and the U.S. Environmental Protection Agency. These studies are distinguished by their broad geographic coverage (which includes the Kenai-lower Cook Inlet and the Kodiak-Alaskan Peninsula areas as well as Prince William Sound), their statistically sound sampling schemes, and by their focus on the mechanistic interactions among species populations that control community response and recovery.

The *Exxon Valdez* oil spill caused widespread and intense damage to rockweed (*Fucus*) in the high and mid intertidal zones. Recovery has been slow, in part because this seaweed recruits new plants most effectively within the microenvironment provided by shading and moisture under its own canopy. *Fucus* is the major provider of structural habitat in the Alaskan intertidal zone, so the indirect impacts of the loss and slow recovery of *Fucus* cover are great and may explain several responses in intertidal invertebrate populations.

The intertidal invertebrates exhibited several large declines and some related increases in abundance in response to the *Exxon Valdez* oil spill. Species that were affected include limpets, barnacles, and probably various grazers such as snails. Responses of the intertidal invertebrate communities were not identical in all geographic areas, even within the sheltered rocky shore habitat, but all geographic regions exhibited significant impacts.

Application of pressurized hot water during cleanup of the oil was at least as damaging as the oil itself to intertidal invertebrates and delayed biological recovery. Natural recovery has varied with elevation: the recovery of the high intertidal zone has only recently been initiated, whereas recovery has progressed substantially in the lower zones.

Perhaps the most intriguing yet disturbing outcome of the study of rocky intertidal community response to the oil spill is the demonstration of delayed, indirect effects appearing more than two years after the spill. In a system characterized by strong interactions, such indirect effects are not surprising, and they emphasize the importance of understanding the nexus of interactions among populations involved in response and recovery of marine ecosystems following perturbation.
Subtidal Oil Contamination and Biological Impacts
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The Exxon Valdez oil spill provided a unique opportunity to examine the fate of oil contamination below the water surface, and to study impacts to species and communities in an environment where assessment was generally not confounded by prior pollution. Although subtidal chemical and biological baseline studies prior to the spill were generally absent, comparison between oiled and non-oiled habitats was possible. This paper summarizes the studies measuring oil contamination and biological impacts below the water surface; a habitat which provides a valuable and varied resource base that supports many harvestable species and their prey.

Oil contaminated sediments that are submerged are more difficult to evaluate than intertidal or supratidal sediments. Sediments that are not submerged are often heavily oiled due to direct exposure to oil on the sea-surface resulting from the spill, so that the presence of oil may be visually evident, and biological impacts obvious. In contrast, sub-surface oil is difficult to monitor, contamination is seldom at a concentration level that can be observed visually, and the biological impacts are not as obvious as are the corpses of otters or birds.

On March 24, 1989, approximately 11 million gallons of North Slope crude oil was released into Prince William Sound. In the first few weeks after the spill, about 50% of the oil evaporated or exited Prince William Sound, leaving the remaining 50% within the sound and mostly stranded on beaches (Wolfe et al. 1993). After the first month, the oil on and within the beaches became the reservoir for contaminating adjacent water and subtidal sediments, either through cleaning activities or natural weathering. It is not known precisely how much of the oil entered the water, as soluble compounds or as particulates, nor it is known how much was carried by various mechanisms to submerged sediments.

Low quantities of oil (1-8 ppb total aromatic hydrocarbons) were measured in the water column (Short and Rounds 1993a) in the first two weeks after the spill, when large quantities of oil were floating and moving through the Sound. In later weeks, oil was difficult to detect in direct measurements, but transplanted clean mussels suspended in cages near contaminated beaches accumulated significant concentrations of oil during 30 day in situ tests. Mussels are excellent accumulators of hydrocarbons, have low hydrocarbon metabolizing rates, and indicate that hydrocarbons were available to organisms below the surface. The gas chromatography-mass spectroscopy (GC-MS) profiles of the hydrocarbons in the mussels by Short and Rounds (1993b) indicate that mussels suspended in cages below the surface were exposed to particulate oil, rather than only the lighter fractions with relatively higher water solubility. These tests indicate that petroleum hydrocarbons were biologically available below the surface.

Sediment traps near oiled beaches collected oil-contaminated sediment in
1990 and 1991, indicating that there were physical mechanisms in place to transport low levels of contaminated sediment, probably from intertidal beaches, and deposit them on submerged sediments (Sale et al. 1993). Although the quantities were not acutely toxic, they indicated that oil movement to submerged sediments persisted 1-2 years after the spill.

Hydrocarbon contamination of subtidal sediments was measured inside and outside Prince William Sound (O'Clair et al. 1993) during 1989 and 1990. Subtidal hydrocarbon concentrations were generally less than contaminated beaches, but were readily detected at a variety of sites in Prince William Sound from 0-20 meter depths. Concentrations were usually highest at the shallower depths, and from sites near heavily contaminated beaches, such as Herring Bay. Depths of 40 and 100 meters sometimes had low levels of hydrocarbon contamination, but the analyte profiles were not always similar to Exxon Valdez crude oil. By 1990 there was some indication at some of the heavily contaminated sites that hydrocarbon levels at depth increased. This may be the result of redeposition of weathered oil by natural processes or from extensive cleaning activities moving some of the oil down-slope.

Bacteria numbers in subtidal sediments were significantly greater in oiled areas compared to control sites (Braddock et al. 1993), indicating that the hydrocarbon contamination was providing a substrate for bacterial action. These measurements were made on sediments collected along with the sediments measured by O'Clair et al. (1993). There is a high correlation between the hydrocarbon concentration and the bacterial numbers. Increases in bacterial numbers reflect one of the first processes instrumental in sediment recovery (bacterial degradation of hydrocarbons), but also provides another route of hydrocarbon entry into higher organisms. Access to the petroleum hydrocarbons can be direct by contact with the sediments, or indirect through the food chain.

The composition and density of the meiofauna (small benthic animals) community in intertidal and subtidal sediments varied between oiled and unoiled bays (Shirley et al. 1993). Harpacticoid copepods, which have highest densities in surficial (the upper few millimeters) sediments, generally had lower densities in the intertidal (0 m) zone of oiled bays in initial samples following the spill, but not subtidal (-6 m) sediments. In contrast, the numerically predominate nematodes, which reside deeper in the sediments and are anaerobes, exhibited little effect in abundance.

Field experiments examining meiofauna recolonization in trays of oiled and unoiled sediments found that colonization was rapid for many true meiofaunal taxa (but was much slower for the deeper dwelling nematodes), even in highly oiled sediments. However, the abundance of most taxa, including two harpacticoid species and total copepods, was significantly depressed at high oil dosages early in the experiment, but not after 29 days (Fleeger et al. 1993; Shirley et al. 1993). Differences in colonization rates rather than oil-induced mortality was the apparent cause. However, abundances of a few taxa (e.g., ostracods) remained depressed in highly oiled sediments for more than a year. Differences between oiled and unoiled bays diminished in years subsequent to the spill.

Several subtidal fish species were studied following the spill. Exposure of
fish using the littoral zone (shore or coastal zone), particularly Dolly Varden, was greater in the months following the spill (Varanasi et al. 1992; Collier 1993). A year later, in 1990, Dolly Varden exposure to oil decreased. However, nearshore benthic species (rock sole, yellow fin sole, and flathead sole) continued to be exposed to hydrocarbons. Pacific halibut occurring in depths greater than 30 meters appear to have less exposure than fish found in shallow subtidal areas. Pollock were found to have increased exposure to hydrocarbons even as far as 400 miles from Bligh Reef (Varanasi et al. 1992; Collier 1993). Pink salmon fry collected from oiled areas in 1989 were contaminated with petroleum, particularly in the viscera, but no hydrocarbons were detected in fry collected from the same areas in 1990 (Wertheimer et al. 1993).

Several subtidal communities were affected by the oil spill. Benthic communities in the fjordic portion of Herring Bay showed signs of impact, including declines in species diversity associated with increasing dominance by a single polychaete (worm) species (Jewett et al. 1993a). Populations of leather stars and helmet crabs were much less abundant in oiled areas as compared to non-oiled areas (Dean and Jewett 1993) and eelgrass had lower densities of turions and flowers at oiled sites (Dean et al. 1993).

Predicting recovery of the subtidal zone is complicated by the habitat and species diversity and the varying responses of plant and animal populations to oiling. Also, since the oil tended to move down slope over time, some subtidal communities were affected later than others. Concentrations of oil in some shallow subtidal sediments decreased over time, but other subtidal sediments showed no significant changes during the study period (O'Clair et al. 1993). Eelgrass and some species of subtidal algae appeared to be recovering after being affected by the oil. The free space created by the loss of algae was being re-colonized by new recruits (Dean et al. 1993b). In some eelgrass beds, sensitive burrowing amphipods recovered to near pre-spill densities by 1991 (Jewett and Dean 1993b). Leather stars showed little sign of recovery through 1991 (Dean and Jewett 1993). Helmet crab populations appeared to be changing, but it is unclear if population recovery or immigration from non-oiled areas accounts for the increased abundance of this species in oiled areas.

Oil contamination did reach the water column and the shallow subtidal sediments. The lack of other pollutants in Prince William Sound allows for a suite of unique studies to examine the impacts of low level subsurface oil contamination over time. The oil contamination levels were not acutely toxic like the physically smothering oil that impacted some upper intertidal zones, but the low level contamination did cause increases in bacterial numbers, meiofauna mass and species structure, and did alter several subtidal habitats. There are definite signs of recovery in the habitat studies, yet the low level sediment contamination continues to be detected. The residual oil contamination in beaches and under oiled mussel beds may continue to be a reservoir of oil for redistribution to nearby subtidal habitats for some years to come.

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Plenary Session: Subtidal Contamination and Impacts


Summary of Injuries to Fish and Shellfish Associated with the Exxon Valdez Oil Spill
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On March 24, 1989, the Exxon Valdez oil tanker ran aground on Bligh Reef in Prince William Sound and spilled nearly 11 million gallons of crude oil. In the days and weeks that followed, oil spread across much of Prince William Sound, the waters off the Lower Kenai Peninsula, Afognak Island, Kodiak and the Alaska Peninsula. Birds, otters and seals were obviously in harm’s way, but since oil floats, many thought that fish could swim away from the danger above. Not all could.

Rockfish were the only adult fish found dead following the spill (Andrew G. Hoffman, personal communication). Determining the cause of death in a fish is difficult unless it recovered shortly after the animal has died. Nevertheless, five rockfish were found sufficiently fresh to determine oil as the cause of death. Despite this, most rockfish live at depths that oil was not known to have reached in the first few months following the spill. Nevertheless, demersal rockfish in early May 1989 had significantly higher concentrations of hydrocarbons and hydrocarbon metabolites in their bile in oiled than in non-oiled areas. Over time, more of the heavier fractions did reach these depths and rockfish tissues collected in the fall of 1991 (the most recent samples tested) still showed signs of chronic histopathology (Gary D. Marty, personal communication).

Though rockfish were the only adult fish observed dead following the spill, small intertidal and juvenile fish which may have been killed would not have been noticed in the omnipresent mouse.

It was unfortunate that herring were just beginning their near-shore and intertidal spawning when the oil spill occurred. The oil did not deter them, however, and they spawned on the oiled shores and kelps with their usual abandon. Adults, eggs and juveniles were exposed to oil. The hatching rate was lower, there were more chromosomal aberrations in the larvae and the proportion of viable larvae was lower in the oiled areas (Evelyn D. Biggs, personal communication).

Three years later when the fish in this year class began to mature, they represented the next to smallest recruitment of 3-year olds to the spawning population in 25 years despite that they themselves were the result of a strong year class. Every four to six years, one year class of herring usually recruits to the spawning population at a significantly higher level than other year classes and dominates the spawning population until its numbers decline with time and another large year class takes its place. The 1988 year class was such a class. During the oil spill, the 1988 year class was exposed to oil in its rearing areas. It began to dominate the spawning population in 1992, yet the fertility rate of the eggs it produced was significantly lower in the oiled areas than in the unoiled areas (Richard M. Kocan, personal communication).

During the time of the oil spill, young
salmon were leaving their natal streams and hatcheries for the open ocean. The oil did not seem to diminish the available food for salmon juveniles in the oiled areas (Alexander C. Wertheimer, personal communication), but the extra metabolic energy expended by juveniles to detoxify the water soluble fractions of oil to which they were exposed may have been the cause of slower growth rate found in oiled areas compared to unoiled parts of Prince William Sound (T. Mark Willette, personal communication). Reduced growth rate, according to Willette, results in poorer juvenile to adult survival. This was observed when the following year pink salmon adults returned at half the rate to a hatchery in an oiled area as to hatcheries in the unoiled parts of Prince William Sound.

In the fall of 1989, pink salmon returned to spawn in the intertidal portions of Prince William Sound streams. Where oil was present in the spawning gravel, eggs and fry suffered higher mortalities than in areas of clean gravel (Samuel Sharr, personal communication). The upper region was the most heavily oiled of the intertidal areas, and it was the slowest to be cleaned by tides and waves and other natural scouring actions. The following year, egg and fry mortalities were significantly higher only in the upper intertidal portions of oiled streams. However, in 1991, mortalities in all intertidal regions were higher in the oiled than in the unoiled areas. The same phenomenon appeared in 1992 as well. It is theorized that genetic damage occurred when the adults spawning in 1991 and 1992 were incubating as eggs and fry in oiled gravel two years earlier. Genetic and environmental causes of this apparent functional sterility are currently being investigated (Samuel Sharr and James E. Seeb, personal communication).

Oil was still present in the salmon fishing areas when adult salmon returned in the summer of 1989. Nets could not avoid straining oil and water; oiled nets contaminated the salmon held by them; and oil-tainted salmon could not be sold. Fishing seasons were closed and many more adults returned to some spawning streams than was desired. It appears that the excess sockeye salmon returning to Red Lake on Kodiak Island and to the Kenai River system on the Kenai Peninsula produced more juvenile salmon than the ecosystems' food webs could support (Kenneth E. Tarbox, personal communication, Dana C. Schmidt, personal communication). Apparently, many young fish starved, fewer than normal outmigrated in the following years as smolts and fewer than normal are expected to return as adults; so few in fact, that commercial and sports fishing seasons may be closed. If this happens, hundreds of millions of dollars will be lost from the commercial and sports fishing industries.

In the Kenai system, the effects of other overescapements in the two years prior to the Exxon Valdez oil spill combined with the effect of the 1989 oil spill to severely impact that river system. There has been no indication of recovery to date.

Dolly Varden and cutthroat trout were overwintering in freshwater lakes when the spill occurred in Prince William Sound, but they soon left these lakes to forage in the near shore areas until they once again entered freshwater in the fall. The rocks and sediments of the near-shore areas were coated with oil and long after oil had left the pelagic waters, the near-shore was still contaminated. Some of those areas which were
cleaned by response crews were devoid of life because of the cleaning process. Dolly Varden and cutthroat trout frequenting these areas may have found less food in the cleaned areas and toxic hydrocarbons in the oil-contaminated locations. Subsequent sampling found their growth rates and annual survival were less in the oiled than in the unoiled areas (Kelly R. Hepler, personal communication). Some populations of cutthroat have declined to such critically low levels that these areas are now closed to fishing.

Clams were impacted by some of the methods used to clean the beaches following the oil spill. Many clams on oiled but uncleared beaches survived, but their growth rates appear to be lower than in the unoiled areas (J.D. Johnson, personal communication).

Oil is known to have a very severe impact on crustaceans, but commercial fishing and heavy predation by an expanding sea otter population prior to the Exxon Valdez oil spill made it very difficult or impossible to determine the effect of oil on some species. A dungeness crab project quickly came to an end when only one crab could be found in the impacted area of Prince William Sound (Charles Trowbridge, personal communication). The Green Island area was directly in the path of much of the oil passing through Prince William Sound and it had once been a very productive area for commercial shrimp fishing. But the population crashed before the spill and therefore determining injury due to oil is very difficult. Nevertheless, in the absence of commercial fishing over the last several years, this population has not recovered (Trowbridge, personal communication). As noted earlier, recent evidence suggests that rockfish continue to be exposed to oil. It logically follows that shrimp in the same habitats would also be exposed, but whether this is preventing these populations from recovering is unknown.

The fish and shellfish of the spill areas were impacted by the oil even though they were beneath the surface. Because many of the fish and shellfish examined are commercially important species, it has often been difficult to separate the effects of oil from fishing mortality. Nevertheless, within sometimes broad boundaries, it has been shown that even the adult populations of fish and shellfish were affected by impacts even to the juvenile stages of these animals. Restoration considerations are warranted and may be necessary in order to bring some of these stocks back to healthy levels.
How Do You Fix the Loss of Half a Million Birds?
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The Exxon Valdez Oil Spill occurred at the end of March 1989, near the end of winter when thousands of Bald Eagles and loons, plus countless waterfowl and seabirds were overwintering in Prince William Sound. The oil spread slowly at first, then high winds blew the oil quickly southwest across the Sound into sheltered bays and fjords densely populated by sea otters, harbor seals and birds. The oil filled bays acted as a trap for birds flying into the sheltered coves to roost for the night. Western Prince William Sound became a dead zone overnight.

The wind continued blowing the oil out of the Sound into the Gulf of Alaska and along the Kenai Coast fouling the headlands and disrupting the birds at the Chiswell Islands, but luckily causing relatively little injury to the seabird populations there.

In early April oil reached the Barren Islands just prior to the beginning of nesting by Common Murres on the seabird breeding cliffs. Many tens of thousands of breeding Common Murres had gathered in large rafts adjacent to the islands and the oil swept away the great majority of these birds. Prior to the spill the breeding colonies on the Barren Islands were home to approximately 130,000 birds, but 60-80 percent were engulfed, carried away and killed by the oil. Many of the carcasses drifted ashore on the Alaska Peninsula in April and May, and many carcasses undoubtedly drifted into the Gulf of Alaska and sank without ever reaching shore.

The timing of the oil surrounding the Barrens could not have been more devastating to the murres, but it fortunately did not kill any puffins or storm petrels which also breed there in large numbers. Luckily, storm petrels and puffins normally do not return to the breeding colonies until mid May, and most of the oil had drifted away from the Barren Islands before these birds arrived at the colony. Almost certainly, some individuals of these species were killed at sea in the Gulf of Alaska and Shelikof Straits, with little likelihood of the birds being recovered on shore.

The oil continued past the Barrens, both eddying into Cook Inlet and Kachemak Bay, and continuing south into the Gulf of Alaska and Shelikof Strait, oiling beaches on the east and west sides of Afognak and Kodiak Islands.

During the initial response phase about 36,000 birds were recovered dead from beaches, and an additional 1,604 live, oiled birds were taken to rescue centers in Valdez, Seward, Homer and Kodiak for cleaning and rehabilitation. Eight hundred and one of these birds were successfully cleaned and released back to the wild. Their survival was not assessed.

Some of the 36,000 birds found dead on beaches in the late summer of 1989 undoubtedly were natural mortality not associated with the oil spill, but only a very small proportion of the oiled birds were ever recovered from the more than 1,300 miles of oiled beaches. Several factors contributed to the small percentage carcass recovery. Many birds were
killed, became waterlogged and sank before reaching shore, and some may have been washed from shore along with oil during the tidal cycles. Other birds were scavenged by eagles, ravens and gulls or by foxes and bears attracted to the beaches because of the carcasses present. Radio marked carcasses put out as part of the Damage Assessment remained on beaches only an average of 24 hours, with most of the carcasses being carried inland by scavengers patrolling the beaches. Many carcasses may have been buried in the beaches by wave action, and many miles of beach were searched only rarely by personnel retrieving carcasses. Small birds were probably missed, and many oiled birds still alive when they reached shore may have lurched up the beach and hidden in the undergrowth to avoid detection by beach walkers, cleanup workers or predators. The Trustees’ extrapolation of the number of birds oiled in the spill is necessarily uncertain, but indicates very strongly that 350,000 to 500,000 birds were trapped and carried by the advancing oil as it swept out of Prince William Sound across the Gulf of Alaska and against the Alaska Peninsula. How many additional birds were carried into the Gulf of Alaska is unknown.

Because Prince William Sound is an overwintering area for birds which migrate away from the spill zone to breed elsewhere, it was not possible in 1989 to accurately assess the numbers of birds present during the spill event. Loons, several species of seaducks, many tens of thousands of migrating shorebirds and thousands of Bald Eagles were all present during the initial time of the spill, but most left the spill area to breed elsewhere. The number of migrants killed and the proportion of these birds that were lightly oiled and suffered reproductive problems is unknown. The spill area was too large to be able to accurately assess the number of birds at risk.

Birds staying in the spill zone remained at risk of exposure for a very long time. Hundreds of miles of beaches became oiled, and a substantial portion of the oil remained aground, but much oil bled from the beaches with each high tide cycle. The ten to 15 foot tidal excursion in Prince William Sound insured maximal intertidal exposure and penetration of oil into the coarse cobblestone beaches throughout much of the spill area. While most of the oil washed ashore or sank, some oil continually bled from beaches for months posing a risk to birds on the water. More insidious, however, was oil contaminating intertidal invertebrates and fish eggs needed as food by migratory and breeding birds. The persistence of oil in mussel beds and intertidal seaweed beds in some places has lasted for years, with continued exposure to species such as Harlequin Ducks, oystercatchers, and some gulls such as Black-legged Kittiwakes and Mew Gulls. In 1989, kitiwakes used seaweed (primarily Fucus) to build their nests and the oil contaminated eggs. Reproductive failure of some kitiwake colonies may have been related to oil exposure.

The extensive cleanup activities in 1989 (and to a lesser extent in 1990) caused disturbance of potential breeding birds in addition to the mortality of directly oiled birds. Bald Eagles, Marbled Murrelets, Pigeon Guillemots, Harlequin Ducks and Black Oystercatchers all suffered breeding losses as a result of oiling, disturbance, or a combination of the two in 1989 and 1990.

Over the past 3 years, the injury suffered by most species appears to have
ended with the cleanup of oil, and many species have apparently returned to normal breeding, but by a reduced population. Marbled Murrelets and Bald Eagles appear to have returned to normal breeding, but Black-legged Kittiwakes have not been carefully monitored since 1989.

Some species, however, are still suffering continued injury. Black Oystercatchers, Harlequin Ducks and Pigeon Guillemots are heavily dependent upon the nearshore and intertidal environments and showed injury in 1990 and 1991. Results of the 1992 breeding season were not available for all species at the time of this writing, but Harlequin Ducks certainly showed continuing injury.

The largest scale continuing injury to reproduction in birds is with Common Murres. These seabirds breed in very dense colonies in only a few locations, and the large colonies at the Barren Islands, and the Alaska Peninsula (Puale Bay and Ugaiushak Island) suffered such great mortality in 1989 that their social structure and organization remain severely disrupted. Many young birds, apparently attempting to breed for the first time at age 4 or 5 years, have returned, but the courtship and egg laying patterns of the birds are poorly synchronized and occur nearly a month later than they should each year. The fragmented, late breeding has resulted in increased predation of eggs and chicks by gulls and ravens, and the winter storms have swept more than 100,000 young chicks off the cliffs to their deaths because the breeding has been so late in 1990, 1991 and 1992. The continuing abnormal breeding at these colonies is very disturbing, as the murres appear to be in real danger of becoming permanently entrained to late breeding, possibly because young birds have established the wrong patterns. If this is permanent, the prospects for these colonies is poor, because a breeding failure will lead to the eventual decline and extinction of these colonies. Many hundreds of thousands of additional Common Murres will be lost if this injury continues. Some bold restoration efforts must be attempted to try to reverse the trend with Common Murres.

Restoration opportunities by the Trustees have been made possible by the unprecedented settlement with Exxon after the spill. The 900 million dollars should provide funding for many diverse projects which have been proposed. The Trustees now have the opportunity to try many innovative new techniques to assist the species showing severe or continuing injury.

Much of the pristine old growth forest of Prince William Sound, the Kenai Peninsula and Afognak Island is privately owned and available for logging, with potential to harm breeding Marbled Murrelets, Harlequin Ducks and Bald Eagles. Protection of these breeding habitats is important, and a substantial proportion of settlement monies should be used to acquire valuable forest parcels in imminent threat of logging.

More important, however, is the need to help restore normal breeding to Harlequin Ducks and Black Oystercatchers and to assist Common Murre and Black-legged Kittiwake colonies suffering breeding failure. Careful cleaning and restoration of specific intertidal feeding habitats, including restoration of mussel beds and seaweed beds is essential. Without this intertidal food base, recovery of the birds and sea otters dependent upon them will not occur normally. The murre and kittiwake colonies remain the most
difficult to help. Control of predators, both foxes and some bird species, should help prevent further losses, but active measures are also needed for murres. Since the breeding synchrony and timing are still wrong at some colonies, drastic measures are called for to assist these fragile colonies. Restoration of colonies of closely related birds has been accomplished in Maine and the Galapagos by placing decoys and playing recordings of courtship calls over loudspeakers to stimulate the birds to begin breeding at the correct time. These techniques should be tried as pilot projects in Alaska, and if successful, a large program to restore the murre colonies should be attempted.

The Exxon Valdez oil spill injury and settlement were both unprecedented in U.S. history. The recovery efforts should also be bold, and creative in the pioneering spirit of Alaska, especially since Exxon has provided sufficient funds to allow the Trustees the liberty to use many different techniques and projects to help restore this unique place.
Effects of the Exxon Valdez Oil Spill on Marine Mammals in Prince William Sound

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Prince William Sound is a large protected embayment that provides excellent and diverse habitat for a variety of marine mammal species. The most common of these species are sea otters, harbor seals, killer whales, humpback whales, Steller sea lions and harbor and Dall’s porpoises. When the *T/V Exxon Valdez* spilled 11 million gallons of crude oil in Prince William Sound on 24 March 1989, many of these marine mammals swam or crawled through oil and inhaled aromatic hydrocarbons as they breathed at the air/water interface. Harbor seals and sea otters rested on oiled rocks and algae. Seal and sea otter pups were born on oiled substrate and nursed on oiled mothers. The prey of some species were contaminated by oil, and this food chain contamination may have lasted for some time after the spill.

Shortly after the spill occurred, studies were initiated to assess its effects on marine mammals that were likely to be impacted. For some species, baseline data on abundance, seasonal distribution, natural mortality, and reproduction were so incomplete or lacking that it was difficult to conduct meaningful studies (e.g., harbor and Dall’s porpoises). Others, such as sea lions, were present for only a short period after the *Exxon Valdez* spill and then moved away as part of their annual cycle, and it was not possible to track which animals had been in contact with the spill. For all species, an undetermined but significant amount of time is spent underwater, making them difficult to count and observe. For some, ongoing declines (harbor seals) or fishery interactions (killer whales) made interpretation of results difficult. Because of the inadequacies of comparative data and study methodology, many of the effects of the *Exxon Valdez* oil spill may never be known definitively. Findings of the major studies are presented here.

Humpback whales are present and feed in Prince William Sound from spring through autumn. In order to assess the impacts of the spill on humpbacks, photographs of individual whales in Prince William Sound were collected from May to September 1989-1990. Research vessels traversed over 20,000 nm in search of whales during the two field seasons. Photographic analysis of Prince William Sound humpbacks revealed 59 identifiable whales in 119 encounters in 1989 and 66 whales in 201 encounters in 1990. No measurable decline in the number of humpbacks occupying Prince William Sound occurred following the *Exxon Valdez* oil spill. Fewer humpbacks used the Lower Knight Island Passage area in 1989 than in 1988 or 1990. Increased vessel and aircraft traffic associated with cleanup activities in that area may have caused redistribution to other areas. No observations were made of humpbacks
swimming through oil. There were no reports of dead, stranded humpbacks during the 1989 or 1990 field seasons.

Approximately 245 "resident" and 52 "transient" killer whales were known to use Prince William Sound prior to the oil spill. In order to assess the impact of the Exxon Valdez oil spill on killer whales, a photographic identification study of individual killer whales was conducted in Prince William Sound during 1989-1992. During the study, a maximum of nine resident pods (148 whales) and four transient pods (34 whales) was documented. Following the Exxon Valdez oil spill, five different pods of killer whales were seen swimming through oil, and killer whales were also observed rubbing on an oiled beach. Analysis of photographs of resident pods in 1989 revealed two animals missing from AE pod, 22 missing from AN pod, and seven missing from AB pod. Losses from AE pod were within the expected mortality rate. The 22 animals missing from AN pod may have belonged to a subgroup that travelled separately from the main pod in 1989; the missing animals were seen again in 1990. During 1990-1991, no additional animals were documented to be missing from resident pods other than AB pod, which lost an additional seven animals. However, in 1990-1991, ten (and possibly eleven) killer whales were missing from transient pod AT. Three of these missing animals were photographed very close to the Exxon Valdez on or about 27 March 1989.

The loss of animals from AB pod in 1989-1991 is unusual and higher than normal mortality would explain. These losses translate to mortality rates of 19.4% in 1989-1989 and 20.7% in 1989-1990, compared to 3.1% in 1988, 4.3% in 1991, and 0 in 1992. No calves were observed in AB pod in either 1989 or 1990. A single calf was seen in 1991 and two calves in 1992. All other resident pods in Prince William Sound have maintained or increased their numbers since 1988.

Harbor seals occur in Prince William Sound throughout the year, particularly in the coastal zone, where they feed and haulout to rest, pup and molt. Some of the largest haulouts in the Sound, and waters adjacent to those haulouts, were directly impacted by oil. In oiled areas of Prince William Sound, 50%-100% of the seals and their pups became oiled. Seals did not appear to avoid oil in the water or on haulouts. Oiled seals in oiled areas were reported to be sick, lethargic, or unusually tame.

Microscopic examination of tissues from seals collected following the Exxon Valdez oil spill found debilitating lesions in the brains of oiled seals. Exposure to aromatic hydrocarbons caused swelling and degeneration of nerve axons, which could have made it very difficult for seals to perform normal tasks such as swimming, diving, and feeding. Hydrocarbon metabolites in bile were 7-13 times higher in seals collected from oiled parts of Prince William Sound than in those from the Gulf of Alaska. This confirms that seals took oil into their bodies through contact, inhalation, and/or ingestion. Because seals have enzyme systems that allow them to detoxify and excrete hydrocarbons, the levels found in most tissues were very low. Highest levels occurred in blubber and in milk.

Aerial surveys conducted in 1989-1992 showed that pup production was lower in oiled areas during 1989 than in 1990-1992, while in unoiled areas it was the same. Based on aerial surveys and carcass counts, neonatal pup mortality was estimated to be over 20% in some
oiled areas. Prior to the Exxon Valdez oil spill, there was an ongoing decline in the number of seals in Prince William Sound that was similar at oiled and unoiled sites. After the Exxon Valdez spill, counts during the autumn molt showed a much greater decline at oiled sites (45% compared to 8% at unoiled sites). In 1992, there were still 35% fewer seals at oiled trend count sites than in 1988, compared to 18% fewer at unoiled sites, indicating that recovery has not occurred.

The number of dead seals found and reported greatly underestimates the number that died, since dead seals do not float but sink to the bottom. Therefore, the number of seals that died as a result of the Exxon Valdez oil spill was estimated based on aerial surveys conducted during the molt.

Based on the assumption that the trend in numbers at unoiled sites was “normal” and that any greater decline at the oiled sites was due to the oil spill, calculations indicate that there were approximately 350 fewer seals in Prince William Sound than would have been expected if the Exxon Valdez spill had not occurred.

Sea otters are widespread throughout Prince William Sound and they were severely damaged as a result of the Exxon Valdez oil spill. They rely on their fur to keep them warm, and consequently they were particularly vulnerable to oiling which destroyed its insulative value. They ingested large amounts of oil as they attempted to clean their fur by grooming. Carcasses of 781 sea otters that were judged to have died because of the Exxon Valdez spill were recovered in or adjacent to the oil spill area, with 424 of those from Prince William Sound. An additional 123 otters died at rehabilitation centers. More sea otters were undoubtedly oiled and died, but their carcasses were not recovered. It is estimated that total sea otter mortality in Prince William Sound was over 2,000, and that in the entire spill area mortality may have exceeded 4,000. Necropsies of otters that died following the spill indicated a high incidence of pulmonary emphysema and gastrointestinal hemorrhage, in addition to kidney and liver damage.

An unusually high proportion of prime-age adults died in both the spill year and in post-spill years relative to pre-spill years. Before the spill, mortality was highest in juveniles (45%) and aged (40%) individuals, and relatively low (15%) in prime-age adults. Following the spill and continuing through 1991, mortality of prime-age adults increased to 43-44%. This suggests that there are prolonged, spill-related effects on the sea otter population as a result of the Exxon Valdez oil spill.

Pre-spill and post-spill boat-based surveys indicated that between 1984-1985 and 1989-1990, sea otter abundance increased 13% in unoiled areas compared to a 35% decrease in oiled areas. By 1991, otter abundance in oiled areas had apparently stabilized, but was still below pre-spill levels.
Restoration Planning Following the Exxon Valdez Oil Spill

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The restoration planning process following the Exxon Valdez oil spill has focused on identifying, evaluating, and integrating information about the nature, extent, and persistence of injuries to natural resources and services, the rate and adequacy of natural recovery, and the opportunities for restoration. This process changes as new information is received, but will culminate in the publication of a Draft Restoration Plan in Spring 1993. The damage assessment and restoration science studies are the primary sources of information on injuries; other sources include data collected during the oil spill cleanup, public comments, and the scientific literature.

This paper reviews the planning approach taken by the Restoration Planning Work Group on behalf of the Exxon Valdez Oil Spill Trustees to identify and evaluate restoration options for inclusion in the draft restoration plan. I also provide a brief vision of how the plan may be implemented, once public comment has been considered.

Identification of Restoration Options

The restoration planning process has identified the widest possible range of restoration ideas, based on suggestions from a public symposium (RPWG, 1990a), public “scoping” meetings (RPWG, 1990b), and a technical workshop (unpublished). Restoration ideas have been organized into restoration options and databases necessary for their evaluation have been assembled. Thirty-five restoration options were identified and presented to the public in the Exxon Valdez Oil Spill Restoration, Volume 1 - Restoration Framework (Exxon Valdez Oil Spill Trustees, 1992a) for review and comment. Based on public comment as well as additional input from the Trustee Agencies and independent scientific peers, there are presently 32 restoration options being considered for inclusion in the draft restoration plan. Arranged by category of restoration activity, they are:

Management of Human Uses
1. protect archaeological resources,
2. intensify management of fish and shellfish,
3. increase management for fish and shellfish that did not previously require intensive management,
4. reduce disturbance at marine bird colonies and marine haul-out sites and rubbing beaches,
5. reduce harvest by redirecting sport-fishing pressure,
6. create national recreation area or wilderness area,
7. increase management in parks and refuges,
8. seek voluntary restrictions in subsistence harvests of marine and terrestrial mammals and sea ducks,
9. seek restrictions and closures to legal harvests of terrestrial mammals and sea ducks,
10. minimize incidental take of marine birds by commercial fisheries,

Manipulation of Resources
11. preserve archaeological sites and ar-
tifacts.
12. improve freshwater wild salmonid spawning and rearing habitats,
13. create new recreation facilities,
14. eliminate residual oil from important intertidal habitats, e.g., mussel beds,
15. accelerate recovery of upper intertidal (Fucus) zone,
16. supplement subtidal substrates (algal and other) for spawning herring,
17. test feasibility of enhancing murre productivity,
18. eliminate introduced foxes and other predators from islands important to nesting of marine birds,
19. replace fisheries harvest opportunities by establishing alternate salmon runs,

Habitat Protection and Acquisition
20. update and expand the State’s Anadromous Fish Stream Catalog,
21. acquire tidelands,
22. designate protected marine areas,
23. acquire additional marine bird habitats
24. acquire “inholdings” within parks and refuges,
25. protect and acquire upland forests and watersheds,
26. acquire extended buffer strips adjacent to anadromous fish streams,
27. designate and protect “benchmark” monitoring sites,
28. acquire access to sport fishing streams,
29. establish or extend buffer zones for nesting birds,

Other Options
30. test subsistence foods for hydrocarbon contamination,
31. establish a marine environmental institute, and
32. replace (return) archaeological artifacts.

Development of Injury Criteria and Identification of Resources and Services that Warrant Restoration

To decide whether it was appropriate to spend restoration funds on a particular resource or service, criteria were first developed that evaluated available evidence for consequential injury and the adequacy of natural recovery. “Consequential injury” indicates a loss attributable to exposure to Exxon Valdez oil, or otherwise attributable to the oil spill and cleanup. “Loss” for injured natural resources is defined as:
1) significant direct mortality, 2) significant declines in population size or productivity, 3) significant chronic and sublethal effects, or degradation of habitat due to contamination by oil or cleanup.

A natural-resource service has experienced “consequential injury” if the oil spill or associated cleanup has: 1) significantly reduced the physical or biological functions performed by the natural resource, 2) significantly reduced aesthetic, intrinsic, or other indirect uses provided by the natural resources; or in combination with either of these, 3) resulted in the continued presence of oil on lands integral to the use of special purpose lands (i.e., parks and refuges designated by the State of Alaska or Federal Government for the protection and conservation of natural resources and services).

To maximize the benefits of restoration expenditures, the Trustees may consider the effects of natural recovery before investing restoration dollars. In a scientific sense, full ecological recovery has occurred when the flora and fauna are again present in similar numbers, health, and productivity to pre-spill conditions, and there is a full complement of age classes. A fully recovered ecosystem is one which provides the same func-
tions and services as were provided by the pre-spill, uninjured system.

For each injured resource and service, an estimation of the rate of recovery will be made based on the best information available from the damage assessment and restoration-science studies, the scientific literature, and other sources. If it appears that recovery will be nearly complete before the benefits of a restoration study or project can be realized, then the Trustees may determine that spending funds is not justified. However, if it appears that the recovery time will be prolonged, it may be worth implementing technically feasible, cost-effective restoration options.

**Criteria to Evaluate Restoration Options**

To help determine which of the many restoration options are most appropriate and beneficial, the following criteria were developed based largely on the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (42 U.S.C. 9601):

1. potential to improve the rate or degree of recovery,
2. potential to prevent further degradation or decline,
3. technical feasibility,
4. degree to which proposed action benefits more than one resource or service,
5. degree to which proposed action enhances the resource or service,
6. potential for additional injury to either resources or services from implementation of option, and
7. the relationship of expected costs to expected benefits.

These criteria have been used throughout the planning process. All ideas developed from the initial public "scoping" meetings also were screened against these criteria during a preliminary evaluation. Ideas which were not technically feasible, or which could produce significant additional injury upon implementation, were rejected.

**Evaluation of Restoration Options for Identifying and Protecting Marine and Upland Habitats**

Additional steps will be needed to properly evaluate habitat protection and acquisition options. While a final process has not been adopted, the Trustees issued a Restoration Framework Supplement (*Exxon Valdez* Oil Spill Trustees, 1992b) that proposed a detailed habitat protection process for public review and comment. The steps in this process include:

1. identification of key upland habitats that scientific data or other relevant information link to the recovery of injured resources and services. This includes an analysis of imminent threat from development (e.g., logging or mining), that recognizes the need to respond to a proposed change in land use that could foreclose habitat protection or other restoration opportunities.
2. characterization and evaluation of potential impacts from changed land use relative to their effects on recovery of the injured ecosystem and its components; comparative evaluation of recovery strategies not involving acquisition of property rights (e.g., redesignation of land-use classification), including an assessment of protection afforded by existing laws, regulations, or other alternatives.
3. evaluation of cost-effective strategies to achieve restoration objectives for key upland habitats identified through steps one and two above.
Restoration alternatives for resource injuries would be evaluated.
4) willing seller-buyer negotiations with private landowners for property rights, and
5) public management of acquired property rights.

Development of Restoration Alternatives

The draft Restoration Plan will describe a reasonable range of restoration alternatives based on requirements of the National Environmental Policy Act of 1969 (40 CFR 1500-1508). The consequences and impacts of each alternative must be analyzed in an Environmental Impact Statement (EIS) (Council on Environmental Quality, 1986). A programmatic EIS will be published simultaneously with the restoration plan.

Each alternative will consist of several or more (a set) of the restoration options listed above. More than one restoration option can be used to restore any one injured resource or service. One option also could address the restoration of multiple injured resources and services. Each alternative, then, will achieve restoration through a different set of options.

We do not implement all the restoration options listed above because their combined cost would greatly exceed the funds now available. As a consequence, alternatives consisting of different sets of restoration options are constructed for public review. In this way public preferences on the options are collected and the implications of choosing some options over others become evident. After consideration of public comment, the Trustees will choose one or more of the alternatives for implementation.

Six possible restoration alternatives were identified in the Restoration Framework (Exxon Valdez Oil Spill Trustees, 1992), they are presented here for discussion only and do not at this time indicate any preference of the Trustees. They are:

1. No action - This alternative is to undertake no active restoration but to rely on natural recovery to restore the injured ecosystem and its associated services.

2. Management of human uses - The use of existing State of Alaska and Federal Management authorities to modify human uses of injured resources or services is emphasized in this alternative.

3. Manipulation of resources or services - This alternative focuses on measures taken directly (usually on-site) to rehabilitate or replace an injured species, restore a damaged habitat or enhance services provided by a damaged resource.

4. Habitat Protection and Acquisition - This alternative includes changes in management practices on private and public lands and the creation of "protected" areas on existing public lands and on marine waters to prevent further damage to injured resources. Beyond land management practices, damaged habitats or property rights can be acquired short of fee simple title, e.g., purchase of timber rights.

5. Acquisition of equivalent resources - Acquisition of equivalent resources means to compensate for an injured resource by substituting another resource that provides the same or a substantially similar service as the injured resource or service. However, direct restoration approaches (manipulation of resources and services, and habitat protection and acquisition) also can be implemented on an equivalent-resource basis.
6. *Combination alternatives* - Each alternative above may be considered by itself or mixed in a number of ways, depending on priorities and approach. Differences among combination alternatives could be based on the severity of injury, the level (certainty) of knowledge on recovery, the perceived effectiveness of restoration techniques, or where restoration will be implemented. For example, one combination alternative could address restoration of only the most severely injured resources and services that we know are not recovering within the affected area, and that only the most effective direct restoration measures would be used. Another alternative could be less restrictive and address restoration of all injured resources and services, both inside and outside the affected area, and apply all available restoration measures (direct restoration, replacement, acquisition of equivalents, enhancement).

**Monitoring**

Implicit in each alternative is the provision to monitor the recovery of injured resources and services. It would be the objective of this program element to monitor natural recovery as well as recovery aided by restoration. Monitoring also would be designed to detect latent injuries and reveal long-term trends in the health of ecosystems affected by the oil spill. The duration of the monitoring program would depend on the severity of the effects resulting from the spill and the time necessary to establish a trend for recovery.

**Implementation of Plan**

Once the public has commented on the Draft Restoration Plan, the Trustees will select the alternative or alternatives that will constitute the Final Restoration Plan. This document is scheduled for publication in Summer 1993. Restoration at the project level will be consistent with restoration options contained within the selected alternative(s) and will begin with implementation of annual work plans beginning in 1994. Each year there will be a call for ideas (project descriptions) for the next year's annual work plan, as there was in 1992 in anticipation of the 1993 field season. Based on this input, a draft annual work plan will be assembled by the Trustees and circulated for public review and comment. After consideration of public comment and any necessary revision, the annual work plan will be adopted and implemented.

**Funding**

Funding for restoration will come from the $900 million that the Exxon Companies agreed to pay the United States and the State of Alaska over a period of 10 years. The *Exxon Valdez* oil spill, however, resulted in injury to resources that may not recover for generations. The extent of injury and the rate of recovery for some resources and services will not be completely known for decades, well beyond the life of the existing settlement. For these and other reasons, restoration needs will continue well beyond the last scheduled payment in 2001. To address this need, the Trustees are considering a proposal to establish an endowment. An endowment could serve to extend the life of the restoration program providing longer-term (perpetual) support for certain restoration activities, e.g., monitoring and research programs, visitors center, and habitat acquisition. An endowment also offers an opportu-
nity to undertake restoration at a different (slower) pace than would be the case if all funds had to be expended within the 10-year life of the settlement. We may not know if initial restoration is successful for many years which suggests a more cautious approach.

References


Tracking Exxon Valdez Oil from Beach to Deep-Water Sediments of Prince William Sound, Alaska

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Prince William Sound, a large, complex-fjord-type estuarine system, owes its configuration to plate tectonics and multiple episodes of glaciation. Gravel beaches dominate exposed segments of bedrock islands whose steep submarine slopes are covered with gravelly to muddy sediment. Submerged morainal highs consist of relict diamicts, indicating rapid tidal currents that sweep away modern fine sediment. Between bedrock and morainal highs of the fjord floor, numerous deep basins (to water depths of 800 m) contain Holocene diatom-rich mud up to 200 m thick. Minor amounts of coarse sediment are being introduced into the estuary from a few fjord-head deltas and as bottom load from the Copper River Delta through Hinchinbrook Entrance. The dominant sedimentary material accumulating today in this fjord complex is fine suspended sediment which is being deposited in deep sediment sinks throughout the sound at rates that vary from 0.3-0.4 cm/yr (Bothner et al. 1990). Much of the insular slope and the fjord walls are kept bare of fine sediment settling from the water column by complex current circulation within the estuary.

We have undertaken four sediment sampling cruises since the Exxon Valdez oil spill in March 1989. The cruises (May 1989, May 1990, August 1990, and June 1992) were planned to sample the bottom sediment along the spill trajectory to follow the geological fate of the spilled oil. Sediment samples were analyzed for aliphatic and aromatic hydrocarbons.

In May 1989, we sampled bottom sediment at 20 stations along the oil spill trajectory from Bligh Reef southwest through Prince William Sound (15 sites) and along the Kenai Peninsula (5 sites). Each site was chosen after a 3.5 kHz acoustic profile line was run across the prospective sample area (Carlson and Reimnitz, 1990). Most acoustic profile lines over box-core sample sites showed relatively thick accumulations of post-glacial, unconsolidated mud which is accumulating in the deep basins today. Some sites were selected on seafloor highs, and cores from these sites contained pebbly sandy muds, principally a glacial moraine substrate. Oil contamination could not be positively identified in sediment at any of the 15 deep-water sites sampled two months after the spill. Only at one site, near the south end of Prince William Sound, northeast of Latouche Island, did the sediment extract have chemical indicators of possible oil contamination, but the presence of spilled oil could not be verified (Rapp et al., 1990).

Nine deep-water sites, originally sampled in 1989, were occupied 14 months after the spill in May 1990. No visible signs of oil were present in the deep-water sediments, but a consistent increase in the terpane ratios C23/C30 may be a consequence of oil-spill contamination (Kvenvolde, et al., 1991). Relative changes in deep-water samples from 1989 to 1990 in the pristane/phy-
tane ratios suggest changes in the depositional environment which may or may not be due to the effects of the oil spill.

Seventeen months after the spill (August 1990), six islands (Elrington, Knight, Eleanor, Smith, Naked, and Storey) and their insular slopes were investigated (Carlson et al., 1991). We found some oil on all of the beaches we visited. The oil was in a variety of forms including sheens of oil on water that percolated from the beach sediment; thin coatings of oil on sediment or rocks; brown sticky mousse-like patches on sediment and driftwood; and tar or asphalt-like pavements or patches on rocks. In the case of the tar, two chemically similar samples were found about 100 km apart on the beaches of the north side of Storey Island, and on the northwest side of Elrington Island. These tars were not from the Exxon Valdez spill because they had different aliphatic biomarker and aromatic hydrocarbon distributions and markedly heavier carbon-isotopic compositions than either the spill oil or the oiled sediments collected from the beaches visited in August 1990. This tar exhibits the characteristics of oil from the Monterey Formation in California (Kvenvolden et al., in press). The other oil samples have sterane and hopane biomarker distributions similar to those of a spilled North Slope crude oil sample secured from the tanker; however, the oils from the beaches are at various stages of alteration as evidenced by hydrocarbon distributions. For example, alkylation and alkenes, as well as n-alkanes and isoprenoid hydrocarbons, have partly or completely disappeared (Kvenvolden et al., 1991).

After sampling the island beaches, we ran high-resolution acoustic profiles across the adjacent insular slopes and then collected bottom sediment at sites selected from the profiles. Rapid degradation of n-alkanes and isoprenoid hydrocarbons limits their usefulness for tracking oil in shallow or deep water sediment. Some of the biomarker characteristics, such as tricyclic-tetracyclic terpane-triplet patterns and sterane/diasterane distributions, suggest addition of spilled oil to sediment at eleven of the shallow water stations occupied in 1990 (Kvenvolden, et al. 1991). All of these samples are located off beaches that were heavily impacted by North Slope crude oil spilled from the Exxon Valdez. However, none of the shallow water samples contained visible traces of the spilled oil.

Thirty eight months after the oil spill (June 1992), we found oil from the 1989 spill on beaches of Naked, Green, Knight, Evans, and Latouche Islands, as well as tar from other sources. On the same cruise, five deep water sites previously occupied in both 1989 and 1990, were reoccupied. Samples from these beach and deep water stations are currently under investigation.

Prince William Sound circulation is strongly influenced by the Alaska Coastal Current. This current is affected by fresh water discharge which, according to Royer and others (1990), was at a record low in March 1989, the time of the spill. They concluded that the spilled oil advanced through the sound more slowly than it would have in a normal year. Under these conditions of lower discharge, the amount of suspended sediment carried by streams draining the large glaciers bordering the Gulf of Alaska was probably below normal. Floating oil, even after losing volatiles, is
not dense enough to sink, unless bonded to particulate matter. If the amount of particulate matter is low, the probability of bonding decreases. This process might explain the absence of the spill oil in the deep-water samples collected on the 1989 cruise. On the other hand, if the lower fresh-water discharge caused the “flow through” to be slowed, the oil would have more time to attach to sedimentary particles. However, the general absence of oil in the deep sediment sinks two months after the spill suggests that the first scenario is more likely. By the second summer after the spill, there is evidence that traces of oil are migrating from the oil-impacted beaches down the insular slopes, and meager evidence that deep basin sediment is showing some trace amounts of oil contamination. The samples collected in June 1992 should show whether or not hydrocarbon contamination from the March 1989 oil spill has reached the deep-water sediment sinks of the fjord.

References
Characterization of Residual Oil in Prince William Sound, Alaska—3.5 Years Later

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Three and a half years after the T/V Exxon Valdez spill, petroleum still persists on many of the beaches used as study sites in Prince William Sound. Presented are the preliminary results of chemical weathering of residual North Slope crude in an intertidal subarctic environment as viewed from an integrated chemical weathering and physical transport prospective. Residual oil samples collected on various beaches during August 1992 are compared to the original T/V Exxon Valdez cargo oil.

Weathering studies of oil degradation indicate the most resistant components often associated with long-term chronic toxicity are the polycyclic aromatic hydrocarbons (PAHs). These PAH compounds are used as weathering indicators when the normal hydrocarbons are weathered beyond detection. The collection locations were part of a long-term study with the objective of having a close correlation between geological observations and chemical analysis so that interpretations would include an understanding of the physical setting and processes which have contributed to the weathering fates.

Due to the great diversity of beach environments impacted by the T/V Exxon Valdez oil spill, an abundance of trapped oil pockets exposed to various degrees of energy and biological activity were created. These areas of various exposure and energy are defined as microenvironments. The August 1992 sampling covered a variety of microenvironments at Knight, Smith, Perry, Latouche, Block, and Crafton Islands. The types of weathered oil found on these beach surfaces ranged from mousse, asphalt pavements, water surface sheens, to rock stains and flake. The subsurface samples consisted of heavy to light oil residue found in boulder to pebble and sand beach material. This range of oil types indicates significantly different physical, chemical and biological degradation processes are occurring and may have been influenced by natural weathering and the beach cleaning techniques. For clear indications and statistical references to the extent of weathering, the samples were analyzed by detailed GC/MS to characterize and source-fingerprint the residual oils collected.

The GC/MS analysis were completed by selective/multiple ion monitoring, focusing on normal alkanes and PAH compounds such as alkylated dibenzothiophenes, phenanthrenes, naphthobenzothiophenes, pyrenes, and chrysenes, fluoranthene, anthracene, and various benzopyrenes. Several of these components are often associated with long-term chronic toxicity. These PAH compounds comprise less than 2% of original T/V Exxon Valdez oil. GC/MS has the sensitivity and capability of selectively analyzing these compounds by the individual peaks or grouping alkylated compounds. The quantitative results from the analysis have been nor-
malized for the compositional differences related to weathering and highlighted for relative toxicities.

All of the samples collected during August 1992 exhibit some degree of weathering. In general thick residual oil without sediments, such as crevice samples, were only slightly weathered as characterized by evaporative loss of the normal alkanes less than nC-12. Close examination of the nC-17/pristane and nC-18/phytane ratios suggest some selective microbial degradation has occurred. Samples of light oil (oily residue) in coarse beach surface material have been highly weathered, as evident by significant alteration of the normal alkanes by microbial degradation. The PAH profile show considerable depletion of the 2-ring naphthalenes and significant reduction of the 3-ring phenanthrenes and dibenzothiophenes; it is only the C-2 and C-3 alkylated homologues of these compounds that persist. The alkylated naphthobenzothiophene, pyrene and chrysenes appear to be the most persistent aromatic hydrocarbons. Additional contribution of combustion-sourced PAHs were detected in some of the trace level samples.

A general trend is that the rate of degradation is proportional to the concentration of oil in the sample. Subsurface oil and thick oil deposits persist since they are protected from the physical processes which breakup the oil into smaller fragments, creating a greater surface to volume ratio which aids the natural rate of weathering by evaporation, dissolution, photo-oxidation, and biological oxidation (biodegradation). Therefore a major limitation to biodegradation is the availability of oil to the microbial community.
Toxicity of Intertidal and Subtidal Sediments Contaminated by the 
*Exxon Valdez* Oil Spill

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This study was conducted under the auspices of the State-Federal Natural Resources Damage Assessment programs. The study was designed to: a) demonstrate and quantify the toxicity of oiled environmental samples, using standard toxicity tests; and b) determine the extent to which any observed toxicity may be attributed to oxygenated, polar products in weathered oil (versus the parent hydrocarbons found in fresh crude).

To estimate the toxicity potential of sediments oiled by the *Exxon Valdez* oil spill, standardized toxicity tests were applied to intertidal and subtidal sediment samples taken during the cruises of the *Fairweather* in 1989, the *Davidson* in 1990, and *The Big Valley* in 1991. In 1989, the sediment toxicity (EC-50's determined by Microtox®) was significantly rank correlated with hydrocarbon concentration, determined by ultraviolet fluorescence (UVF), in intertidal samples from 42 sites in Prince William Sound and impacted portions of the Gulf of Alaska. Toxicity measured by Microtox® in subtidal (3–20m) sediments also showed a generally decreasing trend with increasing distance from the spill center, as did hydrocarbon concentrations measured by UVF.

Toxicity was estimated in 1990 (21 sites in PWS and 8 outside) and 1991 (14 sites in PWS) with a sediment elutriate test using larval oysters *Crassostrea gigas*, and with a whole sediment test using the amphipod *Ampelisca abdita*. The 1990 toxicity tests with amphipods indicated that: 1) intertidal toxicity was substantially greater than subtidal toxicity; 2) mortality was correlated with hydrocarbon concentrations measured by UVF in intertidal sediments, but not at other depths; and 3) mean mortality for intertidal sediments at ten exposed sites inside of Prince William Sound was significantly higher than for six reference sites. Significant amphipod toxicity (relative to controls) was demonstrated in intertidal sediments from the following sampling sites (all notably oiled, listed in order of declining toxicity): Northwest Bay, Snug Harbor, Block Island, Chugach Bay, Chenega Island, Sleepy Bay, and Tonsina Cove. No statistically significant toxicity was detected in any subtidal sediment samples in 1990, and mean mortalities in subtidal sediments were not significantly different between exposed and reference sites.

In 1991, the mortality of test amphipods relative to controls exhibited a lower range than in 1990 (0–50.5%, compared to 0–98.7%), but because control mortality was lower and less variable than in 1990, the threshold for statistically significant differences from controls occurred at lower levels of mortality. Among the eight oiled sites sampled, significant toxicity to amphipods was found at Snug Harbor (6 & 20 m), Sleepy Bay (0 & 6 m),