Coastal Habitat Injury Assessment: Intertidal Algal Communities

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The Coastal Habitat Injury Assessment program, part of the Natural Resource Damage Assessment plan, investigated the effects of the Exxon Valdez oil spill on the biota of the subtidal, intertidal, and supratidal habitats from Prince William Sound to the Alaskan Peninsula. Here we report the results of a study on the effects of the Exxon Valdez oil spill on the intertidal algal communities.

A random stratified experimental design was used to compare data from matched pairs of oiled and control sites in several different habitats in the three main areas of the spill: Prince William Sound, the Cook Inlet and Kenai Peninsula area (CIK), and the area including Kodiak Island and the Alaskan Peninsula (KAP). Each area was stratified by beach type: sheltered rocky, coarse textured, exposed rocky, and estuarine. Oiled sites were selected randomly from information made available from other agencies (Sundberg et al., 1993). Control sites were selected to match each oiled site using physical criteria such as beach slope, aspect, beach texture, and wave exposure. The overall statistical design was to compare data sets within site pairs and then to compare across all sites of one habitat from an area.

Sites were sampled during the field seasons in 1989 (late summer), 1990 (early summer, late summer) and 1991 (early summer, mid summer). Most sites had six randomly selected vertical transects with 3 quadrats (either 20 cm x 50 or 40 cm x 50 cm) located randomly within the first, second, and third meter drop (MVD) from the high water mark. Percent cover of algal taxa was determined in 1991 from a 40- or 80-point grid in undisturbed (control) quadrats, quadrats cleared of all overstory algae, and quadrats scraped bare. Algae from scraped quadrats at all sampling times were preserved in formalin then sorted and weighed in the laboratory.

Because in all areas the most common alga, especially in the oil-affected upper intertidal, was the rockweed Fucus gardneri Silva, we performed several measurements on collected Fucus specimens to better ascertain potential damage to the population. In the field fertile receptacles were collected from randomly selected Fucus plants to determine the viability of released eggs. Fucus plants collected in cleared quadrats were measured for a variety of attributes including plant length, number and maturity of receptacles, and occurrence of damaged fronds, epiphytes, and regeneration.

Each data set was analyzed by site pair comparisons. Percent data were arcsine-square root transformed and tested for differences by Student's t-test. Fucus attributes were tested using either t-tests or a randomization test developed by WEST, Inc., Cheyenne, WY, from the two-sample randomization test algorithms by Manly (1990). Plate data were tested with a Fisher's exact test (Sokal and Rohlf, 1981). Overall tests of significance were tested with both a Fisher's combined test (Sokal and Rohlf, 1981) and by using Stouffer's consensus test.
In the discussion below all pairs of values are reported with the control value first, followed by the value from the oiled sites, and all p-values were calculated from the Fisher's combined test.

An overview of the data shows that in most habitats in the 3 areas Fucus showed significant differences between the control and oiled sites. However, each meter drop, each habitat, and each area had different patterns.

For the Prince William Sound area Fucus percent cover was significantly less at oiled sites in all habitats in 1991, more than 2 years after the spill. This pattern was found in the upper MVD in exposed rocky sites, in the upper 2 MVD's in both sheltered rocky and estuarine sites and at all 3 MVD's in coarse textured beaches.

For example, in sheltered rocky sites Fucus covered 28.4% of the area in controls, but only 11.3% in the oiled sites ($p < 0.01$) in late summer 1991.

In the CIK area Fucus coverage generally showed more differences between oiled and control sites later in the summer in 1991. In sheltered rocky sites there was greater coverage of Fucus in controls (30.7% vs. 14.0%, $p < 0.01$) in the upper intertidal (1 MVD) but less coverage (16.4 vs. 37.2%, $p < 0.01$) 2 m lower (3 MVD) in coarse textured beaches.

Fucus coverage was not significantly different at any tide level in 1991. In estuarine sites there was greater coverage of Fucus in the upper 2 meters, but less coverage in the lower intertidal at control beaches.

The general pattern of more coverage by Fucus in control sites was repeated in the KAP area in the upper intertidal in sheltered rocky sites, and at all tide levels in coarse textured sites.

The lower coverage of Fucus in oiled sheltered rocky and coarse textured habitats was complemented by the lower biomass of Fucus in the oiled sites in 1991. Fucus biomass averaged 1.2 kg m$^{-2}$ in controls and only 0.36 kg m$^{-2}$ ($p < 0.05$) at oiled sites in the upper intertidal sheltered rocky habitats in Prince William Sound. In coarse textured sites the differences were significant in the lower intertidal (3 MVD) zone (0.62 vs. 0.28 kg m$^{-2}$, $p < 0.05$).

Data from oiled sites indicate that the Fucus plants present in those sites were not as reproductive as those in control sites and suffered from a higher level of epiphyte infestation. The average Fucus plant at oiled sites at the second MVD was longer (2.5 vs. 4.4 cm, $p < 0.05$) due to the absence of smaller plants at the oiled sites. In the upper intertidal in oiled sites the Fucus plants had fewer receptacles (860 vs. 36 m$^{-2}$, $p < 0.01$), fewer receptacles per mature plant (16.5 vs. 9.2, $p < 0.05$), and a lower reproductive index. However, egg viability was not significantly different between plants from control and oiled sites. Fucus from oiled areas had more adult plants with attached epiphytes (10% vs. 54%, $p < 0.01$) with a greater percentage of the area of each plant covered.

Because of the dominance of Fucus in the upper intertidal zones, the values for coverage of total algae and of perennials co-varies with the values for Fucus. The patterns for annuals and ephemerals varied with respect to the habitat and tide level. In Prince William Sound annuals and ephemerals were significantly greater in oiled sites with respect to both biomass and percent cover in rocky habitats in the upper intertidal in 1990 and early in 1991. By the end of the summer in 1991, there were no significant differences in these variables. In coarse tex-
tured sites there were initially no differences in annual and ephemeral coverage, except at the 3 MVD where coverage was higher in control sites. This pattern was retained through the end of the field season in 1991 in Prince William Sound. Estuaries in Prince William Sound had greater coverage of annuals and ephemerals in controls in early summer of 1991, but there were no differences by late summer.

The percent cover by ephemeral and annual algae in CIK in sheltered rocky and estuarine sites was similar to the trend in Prince William Sound but the differences between oiled and control sites persisted to the last visit in 1991. In coarse textured sites there were no differences in the cover of annuals and ephemerals in CIK between oiled and control sites, except for the last visit in 1991 at the 3 MVD where there was a slight trend for more annuals at oiled sites.

The KAP area had no significant differences between control and oiled sites with respect to coverage by annuals and ephemerals at any MVD at any habitat in 1991.

Other algae had varying responses to the oiling. Green algae that appeared to be adversely affected by the oiling and/or subsequent beach treatment (that is, those with percent cover values significantly lower in oiled sites) were bladed greens in all estuarine beaches, Cladophora in sheltered rocky sites in Prince William Sound, and Acrosiphonia in sheltered rocky sites in CIK. Coverage by filamentous browns was less in oiled coarse textured beaches in Prince William Sound and in oiled estuarine sites in Prince William Sound and CIK. Plants identified as Myelophycus/Scytosiphon had lower coverage in Prince William Sound and sheltered rocky oiled sites. Red algae that had lower coverage in oiled sites were Halosaccion, Endocladia/Caulocanthus, Odonthalia, Palmaria, and Polysiphonia in sheltered rocky sites in CIK, Gloiopeltis in sheltered rocky sites in Prince William Sound, Cryptosiphonia in exposed rocky habitats in Prince William Sound, and Neorhodomela in both exposed rocky sites in Prince William Sound and sheltered rocky sites in CIK.

A few algal taxa had greater coverage in the oiled sites than the controls. Members of the Gigartinaceae family had enhanced coverage in exposed rocky sites in Prince William Sound and in sheltered rocky sites in CIK and KAP. Brown algae that followed a similar pattern were Myelophycus/Scytosiphon in exposed rocky sites in Prince William Sound and filamentous browns in coarse textured beaches in CIK. In the red algae, Gloiopeltis had more coverage in oiled sheltered rocky beaches in CIK as did Palmaria in oiled exposed rocky beaches in Prince William Sound. Cryptosiphonia and Odonthalia had higher percent cover in oiled sheltered rocky habitats in KAP.

The Cook Inlet/Kenai area had the highest number of significant differences between oiled and control site pairs in the algal percent cover data. Most of these differences occurred at the sheltered rocky beaches. The Kodiak/Alaska Peninsula area had few significant differences, but many of the taxa that did show differences exhibited higher coverage in oiled sites. All areas had significant differences in the amount of uncolonized substrate. There was significantly more bare rock at oiled sites in all habitats at most tide levels in the three areas.

The perennial alga Fucus was the species most obviously affected by the Exxon
Valdez oil spill, especially in the upper intertidal. As of the end of the summer in 1991 coverage by Fucus was still significantly less in most oiled beaches. Our data indicate that recovery will be limited by the few mature plants in the area since the dispersal of Fucus zygotes is restricted to an effective diameter of 1 to 2 m (McConnaughey, 1985). The presence of a protective canopy is probably also a factor in enhancing the survival of Fucus germlings (van Tamelen and Stekol, 1993). The length of time for the upper intertidal populations of Fucus to recover to the level of the control sites is unknown at present, but will be a function of the rate of dispersal from nearby Fucus beds.

References
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Damage and Recovery Rates of *Fucus* in Herring Bay, Knight Island
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The brown alga *Fucus gardneri* is the most abundant intertidal seaweed in Herring Bay, Knight Island, Prince William Sound, comprising up to 90% of the total algal biomass. The abundance of this plant and its simple and observable life cycle allowed detailed observations and experiments to be carried out regarding the consequences of the *Exxon Valdez* oil spill. Much of Herring Bay was heavily oiled, and a variety of clean-up technologies were performed throughout the bay. However, the southeast arm of the bay received little or no oil, allowing comparisons of oiled and unoiled areas within the same bay. Over three field seasons, 1990-92, we were able to quantify the damage done by the oil spill and associated clean-up to *Fucus* populations in Herring Bay. Using a variety of experimental techniques we also determined some of the factors influencing recovery of *Fucus* populations.

Five pairs of oiled and control sites were monitored, but for brevity and clarity we will report only the results from one representative pair of sites. The pair we will consider are two sheltered rocky sites. The oiled site was heavily oiled and probably received high pressure-hot water clean-up treatment. To assess damage to *Fucus* populations and assess recovery rates, we monitored 18 permanent plots (20x50 cm) at each oiled and control site. There were six randomly located plots in each of three tidal levels. Sampling consisted of estimating percent cover of all sessile organisms using a systematic point contact method. All *Fucus* plants were then measured, and, if they were reproductive, the number of receptacles and stage of development were recorded.

In the upper intertidal, *Fucus* covered about 50% of the area at the control site, while at the oiled site *Fucus* cover was initially about 10%, increasing to about 20% in 1992. None of these differences were statistically significant due to the high variability in the data. In the mid intertidal, initially 80% of the area was occupied by *Fucus* at the control site, compared to 20% at the oiled site. By 1992 these significant differences had converged and were no longer statistically different. The percent cover of ephemeral algae was greater at the oiled site compared to the control. In the mid intertidal, about 20% of the area was initially covered by ephemeral algae, declining to almost none in 1991. Ephemeral algae were always scarce at the control site in the mid intertidal. In the low intertidal, ephemeral algae were initially more than twice as abundant at the oiled site compared to the control site, but this difference disappeared in 1991.

The differences in the percent cover of *Fucus* can be attributed to lower densities of large plants (>10 cm) and reproductive plants at the oiled site. In 1990 and 1991 large plants were almost nonexistent at the oiled site in the upper and mid intertidal. At the control site there were about 5 large plants per quadrat in the upper intertidal and 5-20 in the mid intertidal. In 1992, there were no significant differences between the oiled and
control sites in the number of large plants, but the upper intertidal recovery is not apparent. There were also few reproductive plants at the oiled site in the upper and mid intertidal. At the control site there were about 5 reproductive plants per quadrat at the same two tidal levels.

At the oiled site in the mid intertidal there were more germlings in late 1990 and early 1991. In 1991, there were more small plants and in 1992 there were more medium plants at the oiled site. This year class of plants probably settled the summer after the oil spill in 1989 and have grown into new size classes over the years, increasing the number of plants in subsequently larger size classes. It seems that recovery of Fucus in the mid intertidal is proceeding.

In order to assess the ability of Fucus to recolonize damaged sites the settlement rate of Fucus eggs was estimated. The relative number of Fucus eggs landing on oiled and control beaches was assessed by placing four Plexiglass plates designed to trap Fucus eggs at each of three tidal levels. By scoring the plates with a utility knife, grooves just wider than the diameter of a Fucus egg were made, Fucus eggs settle on the plates, concentrating in the grooves. These plates were left in the field for 24 hours after which the number of eggs on each plate was counted under a dissecting microscope. The 24 hour cycle was repeated for three consecutive days. These observations were performed three times in the summer of 1992. The distance to the nearest fertile Fucus plant was measured during all three sampling periods.

There were almost no eggs collected by the egg catcher plates at the oiled sites throughout the summer. At the control sites egg counts averaged up to 800 eggs per plate per day. This difference in settlement rate can be explained in part by the low density of reproductive plants at oiled sites. The distance to the nearest fertile Fucus plant, which is inversely related to density, was about four times as great in oiled areas.

To assess Fucus recruitment and germling survival, unglazed ceramic plates were made and deployed in the field. These plates were made with grooves of three widths and two depths. Half of the plates were seeded in the lab with Fucus eggs, and the germlings were grown for a month before deployment. Four plates were placed at each of two tidal levels at three oiled and three control sites. After 2 months the number of germlings in each groove was recorded. Areas not in grooves on the plates were also monitored.

Seeded germlings only survived in the grooves of the ceramic tiles, and recruitment only occurred in the grooves. The widest, shallow grooves provided little protection for germlings from detrimental conditions. The narrowest grooves were slightly smaller than Fucus eggs and Fucus did not recruit well to these grooves. Medium-width grooves and deep, wide grooves provided good habitats for young Fucus plants.

Experiments performed in 1991 using petri dishes instead of ceramic plates showed that germlings usually did not survive more than 1 month on flat surfaces. To determine possible mechanisms of this high mortality, the survival, estimated percent cover, of these germlings was compared to the desiccation rate at the site of the petri dishes. Also, four of these dishes were experimentally exposed to whiplash from adult plants. Desiccation rates were greater at oiled sites, and desiccation was negatively cor-
related with percent cover of seeded germings in petri dishes. Where desiccation was greater, Fucus germings were less abundant due to higher mortality. Adult Fucus canopy can lower desiccation stress, potentially enhancing germing survival. However, when germings on plates were placed under Fucus canopy without herbivores and in constant contact with the ocean, very few germings survived after 2 weeks. Whiplash from the adult plants removed the germings from the substrate. By providing a refuge from desiccation and whiplash from adult plants, cracks and crevices in the substrate seem to greatly enhance germing survival.

The growth rates of established Fucus plants were determined by marking randomly chosen individual plants in each of three size categories at three tidal levels. The size categories were 2.0-4.5 cm, 5.0-9.5 cm, and >10 cm. These plants were measured to the nearest 0.5 cm in spring 1991, fall 1991, and summer 1992. New plants were tagged when mortality or loss of tags occurred.

In the upper intertidal in oiled areas Fucus plants in all size classes grew about twice as fast as plants in control sites over a period of 1 year. In the mid intertidal only large plants grew faster in the oiled areas. This indicates that once Fucus plants become established in oiled areas recovery may proceed rapidly.

Results from our experiments and observations showed that large Fucus plants in the upper and mid intertidal showed lower densities in oiled sites compared to control sites. Fewer large plants created less cover of Fucus and more open space for ephemeral algae to colonize. Ephemeral algae showed greater abundances up to 2 years after the spill at oiled sites. Since reproductive Fucus plants are usually at least 10 cm in length, fewer large plants meant lower densities of reproductive Fucus at oiled sites. Since Fucus eggs have limited dispersal, the lack of reproductive plants has led to observed lower Fucus egg settlement at oiled sites. Heterogeneity in settlement substrata was required at both oiled and control sites for recruitment of settled eggs into the Fucus populations. At oiled sites, cracks and crevices reduce the effects of heat and desiccation, while at control sites, whiplash from adult plants was ameliorated by cracks. Thus, surface heterogeneity is almost essential for Fucus to recruit into damaged and unoiled areas. New recruits in upper zones of oiled areas were confined to relatively deep cracks in the rock surface, and casual observations revealed that almost all Fucus plants are found to be attached in cracks.

Due to low settlement rates and severe environmental conditions recruitment of Fucus into areas severely damaged by the oil spill and associated clean-up efforts, particularly the upper intertidal, has been minimal. In areas with less harsh conditions, mid and low intertidal zones, Fucus has recruited abundantly. Once recruited to a damaged area Fucus plants grow faster due to reduced intraspecific competition since few plants remain at oiled sites, especially if those sites were heavily cleaned. Thus, where recruitment has occurred, recovery of Fucus populations is proceeding rapidly. However, where Fucus recruitment is low, recovery has been slow.
Meiofaunal Recolonization Experiment with Oiled Sediments; The Harpacticoid Copepod Assemblage

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To gain insight into the effects of the Exxon Valdez oil spill on the meiofaunai (small organisms living on the ocean floor) of Prince William Sound, Prudhoe Bay crude oil was used in a colonization study initiated in 1990. Sediment, collected near Juneau, Alaska, was repeatedly frozen and thawed, washed with freshwater and sieved through 2 and 0.417 mm screens to kill and remove meiofauna. Prudhoe Bay crude oil was added and mixed into this azoic sediment to reach concentrations of 0.5 and 1.7% crude oil. The resulting mixture was added to replicated colonization trays (13 x 28 x 33 cm). Non-oiled azoic sediments were added to additional trays. Triplicate trays of all treatments were placed flush with the sediment surface on beach transects in a randomized block design near mean low water (-0.6 m) in Herring Bay (a cove that was heavily oiled from the Exxon Valdez spill), Prince William Sound. Trays were sampled by coring on days 0, 1, 2 and 29. Cores were also collected from nearby undisturbed ambient sediments on each collection date, including Day 0, to quantify the colonizing source pool. Here, we report on an analysis of the harpacticoid copepod species from these collections.

Collections of meiofauna taken from azoic sediment prior to placement in the field (Day 0) suggested that although meiofauna were killed, decomposition was incomplete. Copepods, with chitinous cuticles, were especially resistant. Residual copepods in our colonization samples were identified by observation of the condition of the setae of various appendages, with particular attention given to the caudal setae; a large number of broken setae indicated to us that these individuals were dead when collected. Most copepods with broken caudal setae showed signs of decomposition including ruptured cuticles, partially decomposed flesh and a dense detrital coating over the body. All copepods were recorded as “dead” or “alive” at the time of collection based on this observation. Generally, the number of “dead” copepods was roughly equal in all experimental treatments (high, low and control) on all collection dates. An ANOVA conducted on data from Day 29 did not identify an oiled treatment effect suggesting that dead copepods were residuals in all treatments including the controls, and that the density of “dead” copepods was not related to oil-induced mortality. Dead copepods were rare in ambient sediments.

Harpacticoids were diverse with >40 species encountered. The density of copepods increased in ambient sediments throughout the collection period. Highest densities of copepods in colonization trays were also observed in Day 29 collections. Species analysis indicated that sediments and colonization trays were occupied primarily by copepods associ-
at ed with surrounding eel-grass and algal-mat habitats. Most species displayed strongly prehensile first legs, belonging to families associated with a phytal lifestyle. Day 1 and 2 collections demonstrated that colonization was generally rapid (mean densities in trays were similar to those from ambient sediment collections). No single species or succession of species accounted for the rapid colonization; instead colonists belonged to a large number of taxa each found in rather low densities.

A two-way ANOVA was conducted as a randomized block (tray replication was blocked) design. ANOVA treatments were collection day (1, 2 or 29) and oil treatment (control, 0% oil, low, 0.5% oil or high, 1.7% oil). Tests were performed on the total living copepods, unidentified copepodites, and the five most abundant species, two of which were in the Family Diosaccidae, and one each in the Families Canthocamptidae, Laophoniidae and Ectinosomatidae. Collection day effects were significant in all taxa tested reflecting the increase in abundances from Days 1-29 (density in ambient collections increased for the same time). A treatment effect was observed in total copepods, and species designated Canthocamptus sp. and Ectinosomatidae sp. 1. For total copepods and Canthocamptus sp., Tukey’s Studentized Range Test indicated that densities in control and low-oiled sediments did not differ, but that densities in high-oiled sediments were significantly lower than other treatments. For Ectinosomatidae sp. 1, means were significantly different in all experimental treatments, but densities in control sediments were significantly higher than in low-oiled treatments and, in turn, densities in low-oiled were significantly higher than in high-oiled treatments. Our data suggest that differences in colonization rate (either immigration or emigration), rather than oil-induced mortality, were the cause of this difference.

Detrended correspondence analysis was conducted to determine if an oiling effect influenced the copepod assemblage. Results indicate that two axes comprised > 70% of the variance. Axis one contained relatively high levels of variation, with values approaching two standard deviations overall (four indicates complete faunal turnover). All natural samples separated from experiments on axis one and clustered near to each other indicating that experimental trays could be distinguished from the surrounding sediments in species composition on all collections. Other collections were separated on axes 2 with only 1 standard deviation of faunal turnover. Day 1 and 2 low- and high-oiled treatments clustered together as did control, low- and high-oiled sediments from Day 29. Control Day 1 collections were intermediate. Results therefore indicate that an oiling effect was present on Days 1 and 2, but no difference between control and oiled sediments was apparent by Day 29. Species diversity and evenness were similar in all treatments, suggesting that there were no oil-related effect on the number of species colonizing the experimental trays.

Knowledge of the ability of organisms to recolonize an area following an oil spill is vital to understanding the impact of such spills. The response of benthic animals to hydrocarbons varies (Fleeger and Chandler, 1983; Coull and Palmer, 1984; Coull and Chandler, 1992). A combination of effects on mortality, reproduction and migration may all contribute to observed changes in density.
Intertidal: Meiofaunal Recolonization

Our data suggest that copepods have the ability to recolonize aoxic sediments over small spatial scales (many cm²) quickly following the addition of hydrocarbons (see also Alongi et al., 1983; Decker and Fleeger, 1984). Meiofauna are known to be active colonizers through the water column, especially in muddy sediments (Chandler and Fleeger, 1983; Palmer, 1988), and many individuals colonized our experimental trays after one day, even in highly-oil sediments.

However, hydrocarbons, especially at high concentrations, altered colonizing ability. The abundance of two individual species and total copepods was significantly depressed at high-oil dosages. The effect was short-lived however, as a influence of high-oil dosages on community structure was apparent on Days 1 and 2 of the experiment, but not identifiable after 29 days.

We could identify no strong evidence for oil-induced mortality in our colonization trays; the number of “dead” copepods was not different in oiled-compared to non-oiled trays on any collection. Copepods may have avoided the oil-enriched trays or they may have emigrated from the trays at faster rates. Recent data suggest that copepods that have entered the water column have the ability to select specific locations to colonize (Fegley, 1988; Sun and Fleeger unpublished data), but only under low flow conditions.

Emigration rates could also have been affected by hydrocarbons. Copepods under high-oil conditions may display different behaviors; they may have actively emigrated by swimming into the water column or passively emigrated by allowing themselves to be carried away by tidal currents.

In summary, abundance data collected after an oil spill cannot alone determine if migration or birth and death processes are responsible for changes in density. Our data suggest that meiofauna are rapid colonizers, but at high doses of oil, colonization rates are significantly reduced. Better information on the source pool of immigrating copepods is needed to help interpret density changes in a given locale after a spill of the magnitude of the Exxon Valdez.

References
Influence of the Exxon Valdez Oil Spill on Intertidal Algae: Tests of the Effect of Residual Oil on Algal Colonization

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Following the Exxon Valdez oil spill in 1989, we began to study the effects of stranded oil on algal colonization in rocky intertidal communities in Prince William Sound. This knowledge is critical because (1) algae are extremely important structurally and functionally to intertidal communities; (2) there appears to be a predictable succession of organisms following a spill, and enhancement of the early phases could reduce the time to recovery; (3) there is evidence that oil inhibits algal growth (Straughan, 1971); and (4) there is evidence that cleanup measures on rocky shores might even delay recovery, if their biotic effects are as harmful as those of the oil (Thomas, 1978; Foster et al., 1990). As part of recovery from a spill, succession on oiled substrates can differ from natural succession, due to residual toxicity of the oil, large scale mortality that reduces available propagules, and loss of herbivores (Southward and Southward, 1978). We were particularly interested in whether normal mechanisms of colonization were affected by the stranded Exxon Valdez oil, so we examined the initial stages of a succession, the settlement, growth, and early survivorship of algae.

Rocks or tiles were used as substrates for colonization. In 1989, oiled rocks of a similar size were collected from beaches on Knight and Eleanor Islands. In 1990, oiled rocks were collected from the western arm of Herring Bay. In addition, clean rocks were collected from the supratidal zone in southeast Herring Bay, coated with fresh Prudhoe Bay oil, and allowed to weather for a month until the oil was a tarred consistency. Ceramic tiles were similarly prepared with Prudhoe Bay crude oil.

To account for inherent patchiness in algal colonization, we paired oiled and unoiled substrates in each experiment. In addition, the Herring Bay experiments were set up on carefully matched oiled and unoiled beaches. The oiled rocks had one half of the upper surface area cleaned with methylene chloride and oiled tiles were paired with unoiled tiles. All substrates were placed in the rocky intertidal. Prepared rocks from Knight and Eleanor Islands were placed on Gull Island, an unoiled site southeast of the grounding site, and retrieved in 1990. The tiles and the Herring Bay rocks were placed on 6 beaches (3 oiled, 3 unoiled) in Herring Bay and retrieved in 1991. Also in 1991, new oiled and unoiled tiles (unglazed) were placed, ridged side up, on the 6 Herring Bay beaches and a new treatment was added. Half the tile pairs were in cages designed to exclude grazers and half were unprotected. Settlement on these tiles was measured 1992.

In most cases, the oiled sides of rocks and oiled tiles had been colonized by significantly fewer algae than the clean surfaces. On average, algal coverage on oiled sides was less than one third the
coverage on the clean sides. In 1990, for example, the half-cleaned rocks on Gull Island had approximately 70% less algal cover on the oiled sides than the cleaned sides (paired t-test; p=0.001). In Herring Bay in 1991, many of the rocks had been lost, so only the tile data are presented here. For the six beaches, paired t-tests revealed consistently lower algal cover and fewer Fucus germlings on oiled tiles than on unoiled tiles, but at p levels that were generally 0.1 to 0.2. These results prompted the caging experiment in 1991. The 1992 results for the caged tiles also showed a reduction in algal cover, with significant differences (paired t-test; p<0.05) detected at several beaches. For the other beaches, p ranged from 0.06 to 0.17 for Fucus germlings. Testing the combined probabilities from the separate tests (Sokal and Rohlf, 1981) revealed that oil significantly reduced the settlement of Fucus germlings (p<0.001; c² test with 12 d.f.). The effect of oil on settlement on the exposed tiles was not as consistent.

Excluding grazers enhanced the ability to detect statistically significant effects of the oil in Herring Bay. Grazers were not controlled on Gull Island or the 1990 studies in Herring Bay. Grazers feeding preferentially on the oiled sides of rocks and tiles could have accounted for our results. However, we hypothesize that given the susceptibility of grazers to stranded oil (Peltier et al., 1976; Crapp, 1971), the grazers would probably feed preferentially on the unoiled substrates, which would mean we may have underestimated the effect of the oil. Indeed, in our 1991 study, we saw significantly more limpets and littorinids on unoiled tiles than oiled tiles (p<0.001; combined probabilities from separate paired t-tests, c² test with 48 d.f.; Sokal and Rohlf, 1981).

The effect of oil on algal colonization was very pronounced and consistent across a variety of locations in Prince William Sound and from year to year as well as across methods. The two-thirds reduction in percent cover indicates how sensitive this stage of the natural recovery process was to even residual levels of oil. The paired design helped reduce variability due to differences in surface texture of rocks and tiles, and heterogeneity of microenvironments on Gull Island and in Herring Bay. The reduced colonization on oiled substrates in our experiments is similar to that previously described (Nelson, 1981; Notini, 1978; Southward and Southward, 1978), suggesting that inhibition of initial recovery reported from other spills was operating at our sites in Prince William Sound.

References


Variability of Exxon Valdez Hydrocarbon Concentrations in Mussel Bed Sediments
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Concern for mussel beds contaminated by the Exxon Valdez oil spill increased rapidly in 1991 when poor recovery in several predator species was thought to be linked to oiled mussels. A pilot survey confirmed the persistence of Exxon Valdez oil at relatively high concentrations in mussels and underlying sediments in several beds (Babcock et al., these proceedings). The uneven distribution of oil within beds observed during the survey prompted us to sample several beds intensively in 1992 to determine the within-bed variation in sediment hydrocarbon concentrations. In this paper we document concentrations and distribution of hydrocarbons within one bed and examine the effects of several variables.

The study site, on the northern tip of Chenega Island, is fairly typical of highly oiled beds. It is small (approximately 50 m²) and on a low angle beach (4.4% slope) protected from intense wave action by bedrock headlands. Tidal range occupied by the bed is approximately 1.43 m to 1.77 m above mean lower low water. Mussel densities average 1900 animals per m² on sediments ranging from small pea gravel to fine silt.

At each of the 15 subsites within this bed, mussel density was determined and sediments entrained in the mussel byssal mat (threadlike mass holding mussels together), and sediments under this mat to a depth of 2 cm were sampled for hydrocarbons. All sediment samples were extracted and analyzed by UV spectrophotometry at the Auke Bay Laboratory. This method, adapted from Krahm (1991), approximates total oil concentrations based on the concentrations of two and three ring aromatic compounds that fluoresce at the phenanthrene wavelengths (260/380 nm). Although analytical results are not strictly quantitative and can not be compared with results produced by GC-MS analysis, they are extremely useful in comparing large numbers of samples.

Oil concentrations in sediments underlying the mussel bed were highly variable, ranging from 20 µg/g wet weight to 40,498 µg/g with a mean of 13,662 µg/g (S.D. = 13,326 µg/g). The effects of position on the beach and depth were tested with a three way ANOVA (beach position has two components: y axis represents tidal height, x axis is at right angles to y and represents distance from the bed’s central axis). Oil concentrations were significantly greater (P<.05) at the two lower tidal heights, 1.50 m and 1.59 m; mean oil concentrations were 25,778 µg/g and 26,403 µg/g respectively. At the upper tidal height, 1.73 m, mean oil concentration was 1515 µg/g. A two way split plot analysis, treating the two sediment depths sampled at a subsite as two treatments applied to one plot, determined that at each subsite oil concentrations in byssal mat sediments (mean=9383µg/g) were significantly lower than in sediments collected below.
Mussel densities ranged from 15 to 244 animals per sample quadrat (625 cm$^2$) with a mean of 120 mussels per quadrat (1900 per m$^2$) (S.D. = 72). The ANOVA found no significant relationship between mussel density and oil concentrations in either byssal or underlying sediments. This finding is not at odds with the idea that mussels insulate underlying sediment hydrocarbons from tidal flushing. The stability provided by even a sparse mussel cover may be sufficient to allow high levels of hydrocarbons to persist in sediments.

Sediments appear to be a complex reservoir of oil that continues to contaminate mussels. The UV analyses of mussel bed sediments have confirmed visual observations that oil in the study bed is unevenly distributed and that concentrations are higher at lower tidal heights and below the byssal mat. Given that the physical distances are minimal between the lower and upper tidal heights and between sediment depths, the apparent effects of both depth and tidal height on oil concentrations may be related to a third factor, sediment grain size. Further analysis will examine these relationships. The variability of mussel hydrocarbon concentrations within a bed and the relationship to contamination in directly underlying sediments will be clarified when GC-MS mussel analyses become available.

Given the current level of contamination three years after the Exxon Valdez spill, the decline of hydrocarbon concentrations in mussel beds to pre-spill levels will be a prolonged process. In monitoring that recovery, sampling must account for high within-bed variability.

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Oiled Mussel Beds Two and Three Years after the Exxon Valdez Oil Spill
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In 1991, two years after the Exxon Valdez oil spill, scientists observed crude oil associated with some mussel beds that still smelled of fresh aromatic hydrocarbons. Coincidentally, biologists observed continued reproductive failure among harlequin ducks and oystercatchers in the spill area, and possible reduced survival among young sea otters and river otters. All of these higher order consumers are dependent on mussels (Mytilus trossulus) for a large portion of their diets.

We conducted surveys to determine the geographic distribution oiled mussel beds and the concentrations of oil in the beds inside Prince William Sound and along the northwestern shoreline of the Gulf of Alaska. Thirteen mussel beds with evidence of oil present were located in Prince William Sound in 1991, and samples of mussels and underlying sediments were taken from each for analysis of aromatic hydrocarbon content.

In 1992, we resampled most of the 1991 sites and located and sampled 46 additional oiled mussel beds in Prince William Sound. At some sites we sampled more than one mussel bed. Cooperating in the survey and sampling were the Alaska Department of Fish & Game, Alaska Department of Environmental Conservation and the U.S. Fish & Wildlife Service.

Sampled oiled mussel beds within Prince William Sound encompassed primarily the Knight Island group but were actually bound by Green Island on the eastern side, Naked Island on the north, Applegate Island on the northwest, and the Fox Farm site on Elrington Island on the south.

Five control sites were also sampled (Barnes Cove on Knight Island, Olsen Bay, Crab Bay on Evans Island, and West Bay on Bligh Island); extensive histories of petroleum hydrocarbon concentrations in mussels and sediments exist for all these control sites.

Forty mussel beds were evaluated on the Kenai Peninsula, Kodiak Island, and in Katmai National Park and Preserve; oil was observed and mussels and sediments sampled at 13 of these sites. Sampled sites ranged from Tonsina Bay on the Kenai Peninsula, to Cape Nukshak in the Katmai National Park and Preserve.

Criteria for sampling mussels and underlying sediments were the appearance and smell of crude oil in the sediments immediately underlying a moderate to dense mussel bed. Triplicate sediment samples (each consisting of a composite of 8-10 subsamples) were taken along a 15-50 m transect line laid through the densest part of the mussel bed, generally 0-2 cm immediately underneath the mussels. Triplicate, pooled mussel samples (20 mussels each) were collected from the same areas as the sediment samples.

The 1991 mussel and sediment samples were analyzed using gas chromatography/mass spectroscopy (GC/MS) and units are reported as µg/g total...
aromatic hydrocarbons. Sediment samples collected in 1992 were analyzed using a UV fluorescence screening procedure adapted from Krahn et al. (1991). Excitation/emission spectra of the extracts were read at the phenanthrene wavelength (260/380 nm), and values reported are µg/g wet weight total oil equivalents (OE). This procedure does not measure individual analytes within a sample, but does approximate total oil concentration and allows comparison of relative oil concentrations between samples. The UV screening permits the rapid analyses of more samples than by the costly GC/MS procedure.

In 1991 samples, the highest total aromatic hydrocarbon concentrations in mussels were collected from Foul Bay on the Western mainland (mean = 10.31±2.9 standard error µg/g dry weight), Bay of Isles on Knight Island (mean = 6.0±1.1) and Northeastern Latouche Island (mean = 3.8±1.3). Highest concentrations of total aromatic hydrocarbons were shown in underlying sediments collected from the north end of Chenega Island (mean = 427±29.4 µg/g wet weight), a tombolo on Eleanor Island (mean = 36.1±24.3) and Bay of Isles (mean = 28.7±9.4).

In sediments samples collected in 1992, 19 mussel beds in Prince William Sound had concentration in excess of 10,000 µg/g wet weight oil equivalents. The UV analyses of sediments collected in 1992 indicated the highest petroleum hydrocarbon concentrations from an islet in Foul Bay (mean = 62,258±1,558 µg/g), a small tombolo on an islet in Herrings Bay (mean = 39,394±8,655), and the eastern shore of Applegate Island (mean = 30,394±1,081). Mean concentrations of sediments from 3 control sites were less than <3 µg/g OE.

Sediments from mussel beds in the Gulf of Alaska show highest levels from Port Dick (mean = 9,122±2,312 OE), Tonsina Bay (8,250±2,793), and Windy Bay (4,645±1,169)—all along the Kenai Peninsula.

No mussel samples collected in 1992 have been analyzed.

The limited data available to compare levels between 1991 and 1992 suggest that petroleum hydrocarbon concentrations in sediments beneath the layer created by moderately to densely packed mussels are relatively unchanged, indicating that natural processes are only slowly cleansing these beds. This means that the mussels will probably experience chronic oil exposure for years.

We have documented 31 mussel beds within Prince William Sound and 9 along the Kenai Peninsula and Alaska Peninsula showing sediment petroleum hydrocarbon levels in excess of 1700 µg/g wet weight oil equivalents. The potential continued contamination of overlying mussels which form an important food source for higher consumers needs to be closely monitored for natural recovery or for possible use of manipulative restoration measures.

References
Determination of Petroleum-Derived Hydrocarbons in Seawater Following the Exxon Valdez Oil Spill II: Analysis of Caged Mussels
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We deployed bay mussels (*Mytilus trossulus*) that were initially free of hydrocarbons in nearshore waters along the path of oil spilled by the *T/V Exxon Valdez* to determine the persistence and the biological availability of petroleum-derived hydrocarbons to living marine resources. Mussels filter substantial volumes of seawater, and may therefore accumulate petroleum hydrocarbons integrated over the transplant period.

Petroleum hydrocarbon-free mussels were collected from Admiralty Island in southeastern Alaska, and were transplanted to 12 locations inside Prince William Sound and to 18 locations outside the Sound for 2 to 6 weeks at depths of 1, 5, and 25 meters at each location. In Prince William Sound, four successive transplants were conducted in both 1989 following the spill and in 1990; two transplants were conducted during 1991.

Three successive transplants to sites along the Kenai Peninsula, Alaska Peninsula, and Kodiak Island occurred in 1989 and 1990. Mussels were retrieved at the end of each transplant period and stored frozen at -20°C for petroleum hydrocarbon analysis.

Transplanted and control mussels were analyzed using single ion mode gas chromatography-mass spectrometry (GCMS/SIM) for the most abundant 2- to 5-ring polynuclear aromatic hydrocarbons (PAH's) in the spilled oil, and using gas chromatography-flame ionization detection for alkane hydrocarbons including pristane, phytane, and the normal alkanes of 10 to 30 carbon atoms.

Results indicate that mussels transplanted along the trajectory of the oil spill accumulated particulate oil at concentrations that decreased with depth, elapsed time after the spill, and distance from heavily oiled beaches. The highest concentration of total PAH's in the transplanted mussels was 5.70±0.358 standard error μg/g wet tissue weight at Herring Bay, 1 meter depth, 1 to 2 months following the spill; at 5 and 25 meter depths, concentrations were 3.17 μg/g and 0.372±0.139 μg/g, respectively. Concentrations of PAH nearly as high at the respective depths were also found at north Smith Island and at Snug Harbor.

The mussel transplant sites at each of these three locations were within 500 m of beaches that had been heavily oiled by the spill. The relative concentrations of PAH and of alkane analytes detected are generally consistent with those of Exxon Valdez oil (EVO), indicating up to 281 μg EVO/g wet tissue weight.

Lower but detectable PAH concentrations were observed at most other transplant locations within PWS, with relative concentrations of PAH and of alkane analytes that are generally consistent with those of EVO. However, the lowest PAH concentrations were found at the control site, Olsen Bay, where total PAH concentrations generally ranged from .010 to .050 μg/g, with relative concentrations that are not consistent with those of EVO.

Concentrations of PAH's consistent
with EVO inside Prince William Sound declined substantially at all locations by late summer 1989. Total PAH concentrations of up to 1.47 µg/g were observed at Herring Bay, and were at least an order of magnitude lower at north Smith Island or at Snug Harbor. Still lower concentrations of total PAH’s consistent with EVO were detected at most of the remaining locations inside Prince William Sound, although not at Olsen Bay.

Low concentrations of PAH’s were sporadically detected at locations where the transplant sites were adjacent to heavily oiled beaches in 1990 and in 1991. Total PAH concentrations of about 0.26 µg/g were detected at 1 m depth at Herring Bay and at Snug Harbor in 1990, while the highest PAH concentrations detected in 1991 were near detection limits.

Petroleum hydrocarbons were detected only sporadically in mussels deployed at locations outside Prince William Sound in 1989, and were generally below detection limits in mussels deployed during 1990 and 1991. This may have been due in part to poorer survival of the mussels transplanted to locations outside Prince William Sound, resulting from longer transport times.

The accumulation of petroleum hydrocarbons by the transplanted mussels in 1989 indicates that particulate petroleum hydrocarbons were generally available to subsurface marine fauna the summer following the spill. These results are consistent with, and support, results of a companion study where direct chemical analyses of subsurface seawater for petroleum hydrocarbon were performed on samples collected 1 to 6 weeks following the spill: both these studies found the highest concentrations of PAH’s attributable to EVO at the 1 m depths of sites adjacent to heavily oiled beaches.

However, comparison of the results of these two studies indicates that the caged mussels may accumulate petroleum hydrocarbons from much lower seawater concentrations than may be detected by direct chemical analysis.
Estimation of the Exposure Concentration of the Seawater Soluble Fraction of Crude Oil from Mussel Tissue Concentrations

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Mussels have been used for many years to monitor petroleum hydrocarbon pollution in the marine environment (Farrington, 1980). Mussels appear to be ideal living monitors as these filter-feeders process large amounts of water, rapidly accumulate oil to high concentrations without apparent toxicity and rapidly purify the accumulated body burden without appreciable metabolism of the oil hydrocarbons when placed in clean seawater. For mussels to be useful in monitoring environmental contamination, the tissue concentrations must accurately reflect the magnitude of contaminants in the water. Despite a large number of studies devoted to quantitating oil hydrocarbon concentrations in mussels as a measure of water pollution, very few laboratory or field studies have attempted to correlate oil concentration in water with tissue concentrations.

Recently, however, a careful study has documented a relationship between water and tissue concentrations (Mason, 1988, 1 & 2). The extensive laboratory data from this study using black mussels and the water soluble fraction of Quatar crude oil were carefully analyzed using a well studied mathematical uptake model which relates the oil in water concentration and the uptake and purification rate constants with tissue concentrations over time. Since the major objective for monitoring mussels is to determine the pollution concentrations in the water, there is a need for a simple method to estimate the exposure concentrations based on tissue concentrations.

The work described in the present paper extends Mason’s methodology to provide a rapid simple method to estimate exposure concentrations of oil in seawater from previously determined oil concentrations in mussel tissue. The uptake period was shortened to 12 hours using small incubation volumes and frequent replacements of the water soluble fraction of Exxon Valdez crude oil to better provide a constant exposure concentration. In addition, the uptake data was analyzed using an equivalent but alternative mathematical uptake model to derive the uptake constants and provide a direct method for estimating exposure concentrations from predetermined concentrations of oil in the mussel tissue (Spacie, 1983).

Mussels (Mytilus edulis) were obtained from Hood Canal, WA, and maintained in 2.5% artificial seawater (Instant Ocean) at 11°C. The water soluble fraction (WSF) of Exxon Valdez crude oil was prepared by shaking 25 ml of oil with one liter of 2.5% artificial seawater for five minutes at 11°C. The phases were allowed to separate for 21-22 hours in the cold and the seawater phase drained from the separatory funnel into a glass stoppered bottle. The WSF was immediately diluted to 0.1%, 1%, and 10% for the mussel experiments.

Fluorescence was used to quantify oil hydrocarbons in unextracted or hexane-extracted water. The samples were excited at 280 nm and the emission read at
374 nm with no barrier filter in a Hitachi MPF-2A analytical fluorescence spectrophotometer (Mason, 1987). Fluorescence was recorded in centimeters of pen deflection. Hydrocarbon concentrations in unextracted water were determined directly by fluorescence for the time course studies on the effect of aeration of the WSF in the absence of mussels. Seawater samples taken from the flasks containing mussels were centrifuged at 1000 x g for 10 minutes at 11°C to remove debris prior to hexane extraction. The volume of water extracted with 5 ml hexane was 40 ml for the 0.1% WSF exposure; 5 ml for the 1% WSF exposure; and 0.5 ml for the 10% WSF exposure.

Hexane extraction was necessary to eliminate nonspecific fluorescence produced by the mussels and to concentrate the hydrocarbons sufficiently to be readable in the fluorimeter. The hydrocarbon concentrations in the hexane fraction of the water taken from the flasks containing mussels were determined by fluorescence from a standard curve of Exxon Valdez crude oil diluted in hexane. The concentration of hydrocarbons in undiluted crude oil was determined to be 600 mg/ml by gravimetric analysis. In addition to the quantitation of hydrocarbons in the WSF by fluorescence, the concentration of aromatic hydrocarbons (AHC) in the C12-C24 range in the WSF preparations was determined by gas chromatography (GC) (Analytical Resources, Inc., Seattle, WA).

Time course experiments with mussels were performed by exposing 10 mussels/flask (approximately 5 g/mussel) to one liter volumes of 0.1%, 1%, and 10% WSF at 11°C. The flasks were gently aerated. The one liter volumes of WSF were completely replaced with fresh WSF every two hours for a total time course of 12 hours. Hydrocarbon concentrations in the water at the end of each two hour incubation were then determined. Since mussel tissue has not been analyzed at this point in time, uptake by the mussels was determined from the amount of hydrocarbons which disappeared from the water over time assuming the disappearance from the water equals uptake by the mussels. Mussels retrieved at two hour intervals were wrapped in aluminum foil and frozen at -20°C for later analysis.

Fluorescence of 2-fold dilutions of the water soluble fraction (WSF) of Exxon Valdez crude oil in 2.5% artificial seawater was directly proportional over a 100-fold range (1:8 - 1:1024 dilution). The regression was statistically significant (r = 0.996, p<0.01). This plot suggests oil hydrocarbons soluble in seawater can be reliably detected at very low concentrations. To determine the concentration of water soluble crude oil in the seawater and in the mussel tissue, a fluorescence standard curve was obtained using 10-fold dilutions of Exxon Valdez oil in hexane. The logarithm of fluorescence was linearly related to the logarithm of the hydrocarbon concentration over a 100-fold range (0.001 - 0.1 µg/ml). The regression was highly significant (r = 0.945, p<0.01). The concentration of oil in the WSF preparations used for the mussel uptake experiments determined from this standard curve were 4.27 µg/ml for the experiments using 0.1% and 10% WSF and 2.35 µg/ml for the experiments using 1% WSF.

The stability of the fluorescent hydrocarbons in the 10% WSF preparation under conditions of aeration was determined by fluorescence. Aeration of the 10% WSF in the absence of mussel resulted in a 6.4%/day loss of fluorescence (r = 0.965, p<0.01) with no statistically
significant loss in the unaerated control over a six day period. In contrast, ten mussels in one liter aerated volumes of 0.1%, 1%, and 10% WSF removed approximately 90% of the fluorescent hydrocarbons in two hours at 11°C. The percentage loss of fluorescent hydrocarbons from the water was similar for each of the six consecutive two hour incubations which constituted an individual 12 hour time course. These results suggest that the uptake rates were rapid and uniform for 0.1%, 1%, and 10% WSF exposures throughout the 12 hour uptake period and saturation was not evident.

The petroleum hydrocarbon concentrations remaining in the hexane extracted water were determined from the oil in hexane standard curve using fluorescence. By assuming the loss of fluorescent hydrocarbons from the water equaled the accumulation of oil hydrocarbons in the mussel tissue, uptake values for mussels could be calculated. The tissue mass was taken to be 50 grams. For the three 12 hour time courses with complete renewal of the WSF at two hour intervals, the accumulated 12 hour uptake values for 0.1%, 1%, and 10% WSF were 0.442, 2.80, and 44.7 µg oil/gm wet weight mussel tissue respectively.

Uptake constants for the three exposure concentrations were determined graphically by plotting µg oil/gm weight against the relation 1 - e^{-kt} (plot 1) or by plotting µg oil/gm wet weight against c_{in}t (plot 2). In plot 1, e is the base of natural logarithms; k, is the depuration rate constant in day^{-1}; and t is time in days. In plot 2, c_{in} is the concentration of oil in the WSF in µg/ml and t is time in days. Both types of uptake plots have unique and valuable features. In plot 1, the slope of the least squares linear regression line is \((k_{2}/k_{1})(c_{in})\) which can be used to calculate \(k_{2}\), the uptake rate constant knowing \(k_{2}\) and \(c_{in}\). In addition, the slope in plot 1 is equal to the maximum concentration of oil that can be accumulated by the mussels. In plot 2, the slope of the least squares regression line is \(k_{1}\), the uptake rate constant. Plot 2 differs from plot 1 as it does not depend on knowledge of \(k_{2}\), the depuration rate constant. In addition, the exposure concentration, \(c_{in}\), can be estimated directly from this graph if the exposure time, t, is known.

The least squares linear regression lines were statistically significant in both plot 1 and plot 2 for each of the three exposure concentrations using the uptake values for the six time points for each plot. For plot 1, the literature value of \(k_{2} = 0.15\) was used (Mason, 1988, L). The uptake constants were 222, 249, and 219 day^{-1} for plot 1 and 212, 238, and 209 day^{-1} for plot 2 for 0.1%, 1%, and 10% WSF exposures respectively. The maximum uptake values derived from the slopes of the linear regression lines for uptake values in µg oil/gm wet weight plotted against 1 - e^{-kt} (plot 1) were 6.3, 39, and 622 µg oil/gm wet weight for 0.1%, 1%, and 10% WSF exposures respectively. These data confirm that tissue concentrations in mussels are directly related to the product of exposure concentration and time; the uptake constants are independent of exposure concentrations; and the two methods of plotting the uptake data are mathematically equivalent for determining the uptake constants.

The concentration of aromatic hydrocarbons (AHC) in the water associated with mussels taken from sites in Prince William Sound were estimated using our laboratory uptake curves. Tissue concentrations of AHC were determined in
triplicate by the Auke Bay Laboratory using GC and reported in Fish/Shellfish Study #11 (Injury to Herring). The mussels were retrieved between 4/28/89 and 5/4/89 from Fairmont Bay (5 transects); Naked Island (14 transects); Storey Island (2 transects); and Rocky Bay (4 transects).

The mean ± SD values for the tissue concentrations for the indicated number of transects for the four sites were 0.1047 ± 0.0404, 0.6955 ± 0.6227, 0.8445 ± 0.5518, and 1.256 ± 0.995 µg AHC/gm wet weight, respectively. The corresponding mean ± SD values for µg AHC/liter (PPB) using our laboratory uptake curves converted to GC values for the 0.1% WSF exposure were 0.493 ± 0.190 (FB); 3.273 ± 2.930 (NT); 3.974 ± 2.597 (SI); and 5.911 ± 4.493 (RB), respectively, for a one day exposure. The elevated values for AHC in the water or in the mussels at the oiled sites relative to Fairmont Bay values were significant by the t-test (p<0.05). Similar values were obtained from the uptake curve conducted with 1% WSF or 10% WSF.

The predicted concentrations of AHC/ml indicate that significant but low levels of oil pollution were present at selected sites in Prince William Sound 4-5 weeks after the oil spill. The estimated aromatic hydrocarbon concentrations in the water at the sites may be high as the predicted values rest on the assumption of a 24-hour site exposure. Longer exposure periods would proportionately decrease the AHD values in the water. In addition, the high fluorescence to GC conversion factor we determined (8.9) could exaggerate the predicted values. Finally, oil droplets trapped in the prepared WSF or at the environmental site would also exaggerate the values for AHC in the water. Subject to the confirmation of the oil concentrations in the mussels used for the uptake curve, the rapid and convenient laboratory assay described in this paper may provide a simple method for predicting oil exposure concentrations in water samples from determined oil concentrations in mussel tissue.

References
Impacts to Intertidal Invertebrates in Herring Bay, Prince William Sound, Following the Exxon Valdez Oil Spill

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Intertidal monitoring and experimental studies were carried out in Herring Bay, Knight Island, Prince William Sound (60°N: 147°W) as part of the Coastal Habitat Injury Assessment program (CHIA). Population densities for several species of invertebrates were compared between matched oiled and control sites from 1990 to 1992. Limpets were included because they are important intertidal grazers. The periwinkle, Littorina sitkana, the dog whelk, Nucella spp., and the six-armed starfish, Leptasterias hexactis, were studied because they lack a free-swimming larval stage, and may recover slowly after a large reduction in population over a large area.

The initial study design in Herring Bay was to select a range of sites with different oiling histories, including a non-oiled control site, and oiled sites that were mechanically treated (washed) and bioremediated. Ideally, this combination of sites would have been replicated several times to achieve statistical rigor. However, after surveys in May, 1990, review of data from the Exxon/Federal/State spring shoreline assessments, and detailed discussion with Alaska Department of Environmental Conservation monitors working in Herring Bay, treatment history of specific sites could not be determined with certainty. Therefore, the matched pair design of oiled and non-oiled study sites was adopted and treatment was not included as a variable.

Sites were matched for substrate composition, slope, direction and solar aspect, wave exposure, and common biological communities. Control sites were restricted to the southeast corner of Herring Bay, where ice had prevented oil from entering in the spring of 1989. Most matched oiled sites were located in the lower-mid and western portion of Herring Bay.

In 1990, permanent 50 X 20 cm quadrats were established at five pairs of sites: three sheltered rocky and two sheltered coarse grained beaches. At each site six quadrats were located within each of three tide levels, or meters of vertical drop (MVD), below mean high high water. Within each quadrat, all limpets, Nucella spp., Littorina sitkana and Leptasterias hexactis were counted. In 1991, one additional protected rocky site pair and one coarse-textured oiled beach site, for comparison to an existing control site, were added to the study. In 1992, examination of these quadrats continued and four additional protected rocky site pairs were added. There were only three quadrats per MVD for the pairs added in 1992, but they were randomly established as previously done.

Densities of the limpet, Tectura persona, have remained significantly higher at control sites during the 3-year study period, with this difference pronounced at the 1 and 2 MVD (p<.05, at 5 of the 7 pairs at 1 MVD; p<.01 at 3 of 7 site pairs at 2 MVD, repeated measures ANOVA). Also, the differences in density of T. per-
sona between control and oiled sites tended to increase substantially in 1991. This pattern may have continued into 1992, but is uncertain with only two sample periods for this season.

In sheltered rocky habitats, T. persona is common in the upper intertidal but is not abundant at the third MVD. In contrast, T. persona is reasonably common at the third MVD in coarse textured habitats, and the density remains significantly lower at the oiled site in only one of the three pairs at this tide level (p < 0.04, repeated measures ANOVA). For the four site pairs added in 1992, the data support the general trends seen in the original sites. On both sample dates at the 1 MVD, T. persona densities were significantly lower (p < 0.04, t-Test) at two of the oiled sites, with weak significance (p < 0.17, t-Test) at the remaining pairs. A similar pattern occurred in the second and third MVD, but differences were not consistently significant.

Another limpet, Lottia pelta, is distributed lower on the shore, being more abundant in the second and third MVD. Similar to T. persona, differences in L. pelta densities between control and oiled sites peaked in 1991 for the second MVD at most sites. However, L. pelta appears to be recovering more rapidly than T. persona. L. pelta densities at the four sites established in 1992 were generally greater at control than oiled sites, but were significant in only a few cases.

The periwinkle, Littorina sitkana, was significantly less dense, especially at MVD 2, at four of the seven oiled sites compared to controls over the course of the study (0.0001 = p < 0.03, repeated measures ANOVA). Recovery has been minimal. For the four sites added in 1992, L. sitkana densities tended to be lower at oiled than control sites though differences were not always significant. For example, significantly fewer individuals were found at oiled sites in only 1 of the site pairs at the 2 MVD in the spring but by summer, differences were significant at three of the four pairs (p < 0.05 t-Test).

The dog whelk, Nucella lamellosa, had only sufficient densities for statistical comparison at one of the seven site pairs and there were no differences found over the course of the study. However, density at the oiled site dropped by one-half toward the latter part of the 1990 season, and a similar drop was observed in 1991. However, N. lamellosa densities remained higher at the oiled site compared to the control on both sample dates in 1992.

The other species with direct embryological development, Nucella lima and Leptasterias hexactis, were either not present or found in very low densities, and no differences were observed between site pairs.

Reductions in densities of invertebrates, particularly intertidal grazers such as limpets and periwinkles have been reported for previous oil spills (Nelson-Smith, 1977; Mann and Clark, 1978; Southward and Southward, 1978), and our findings are consistent with these earlier results. Effects from the Exxon Valdez oil spill on the invertebrates in Herring Bay have been variable, but damage has been documented, and recovery remains incomplete in some cases, especially the upper intertidal zone. The loss of Fucus from the 1 MVD is believed to be largely responsible for the inability of limpets to survive there. However, with the exception of T. persona, the other af-
fected invertebrates show populations increases since the spill.

A main hypothesis of the population studies was that brooding invertebrates, such as *Littorina sitkana*, *Nucella* spp. and *Leptasterias*, would suffer greater long term consequences because of limited dispersal, and the potential effect of oil on fecundity and development. Based on the data collected to date, only *L. sitkana* appears to have been slightly affected by oil. In 1990 *L. sitkana* showed significant differences only at the coarse-textured sites, but in subsequent seasons abundances have been reduced at the 1 and 2 MVD of oiled sites, similarly to the changes seen in limpets.

References


Exxon Valdez Oil Spill: Recruitment on Oiled and Non-Oiled Substrates

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As part of the Coastal Habitat Injury Assessment program, intertidal experiments were established in Herring Bay, Knight Island, Prince William Sound (60°N: 147°W) in 1990. Two separate studies, continued through 1992, examined the effect of north slope crude oil on recruitment of barnacles, Fucus germlings and filamentous algae. The effects of oil on algal recruitment are reported in a separate abstract in this symposium.

In 1990 two oiled sites and two control sites of similar character were selected to study recruitment on tarred and clean vertical rock faces. At each site, paired 10 X 10 cm plots were randomly established. One member of each pair was scraped and brushed to remove all visible tar and/or barnacles. The sites were periodically visited and numbers of barnacles and Fucus germlings were noted. In 1991 the study was expanded to include a total of five site pairs and grazing-exclusion cages were added to half of the study plots.

The 1990 data show that barnacle recruitment was initially retarded on the oiled plots at oiled sites, compared to the scraped ones (p<0.05, paired t-Test), but these differences began to fade at several sites over time (p=>0.2, paired t-Test). This trend is most evident with the caged plots. The control sites have had consistently greater densities on the control plots compared to the scraped ones. Fucus germlings began to emerge at control sites in 1990, and only in low density at the oiled sites in 1991. In 1992 Fucus was in greater abundance at oiled sites, and were greater on the unscraped plots (both control and oiled sites) compared to the scraped ones (0.2>p<0.8, paired t-Test).

Densities of grazers (limpets, Littorina sikana, and L. scutulata), were significantly greater at control sites compared to oiled sites in 1991 (p<0.05, ANOVA for four of five site pairs).

In 1992 data analysis was further subdivided to include measurement of surviving adults of Semibalanus, Balanus, and Chthamalus dalli from the previous seasons. Fewer differences were observed in 1992 compared to the previous years for all species and ages. Adult barnacles represent those individuals which have successfully recruited onto scraped plots. Adults are found in greater density at control sites because these were non-oiled individuals alive before the spill and left as controls. However, at the oiled sites, adults have successfully recruited on both plots. Within cages, the density of surviving adults are similar on both oiled and scraped plots. However, uncaged plots, this pattern is reversed. Chthamalus dalli were generally greater on the scraped plots compared to the oiled/control plots.

In a second recruitment study, initiated in 1990, three pairs of oiled and control sites were selected for transplanting oiled substrates. The substrates used were rocks retrieved from an oiled shoreline in Herring Bay, as well as rocks treated with fresh North Slope crude oil,
taken from the T/V Exxon Valdez in 1989. Tarred rocks of similar size were collected from an oiled beach in Herring Bay, and represent a substrate coated with 1-year-old Exxon Valdez Prudhoe Bay crude oil (EV). One-half of each rock was cleaned with the solvent methylene chloride (MeCl₂) to remove the oil (Duncan, et al. 1992a). In addition, rocks approximating the sizes of the EV rocks were collected from a similar, but unoiled, beach. Half of each rock was dipped in fresh Prudhoe Bay Crude (PB) until a "tarred" coating was achieved. These rocks were allowed to dry for several weeks and were handled in a manner identical to the EV rocks.

As a control for possible effects of MeCl₂ on recruitment, half of six unoiled rocks were "cleaned" with MeCl₂ (one rock placed per site). As a control on surface heterogeneity, white clay tiles were included in the experiment as oiled and clean pairs.

At each of the six experimental sites, 12 EV, 12 PB rocks and 6 tile pairs were placed randomly at the elevation contour 2 m below MHHW (Mean Higher High Water, included in the upper intertidal zone). Control rocks for MeCl₂ were also placed at each site. Periodically, settlement by barnacles and macro algae on each surface type was recorded.

In 1991, the study was modified to include nine pairs of red clay tiles at each study site. Six of the pairs consisted of a tarred and a clean tile and half of these pairs had cages constructed around them to exclude grazers. The remaining three pairs consisted of a clean tile and a tile painted black (rather than oiled) as a control for dark coloration and possible temperature differences (Straughan, 1976). The tiles were also randomly placed at the 2-m contour.

Only 2 oiled sites were consistently colonized over the three year period (Sites 1322X & 1723X). Control sites received fewer recruits of all species (except for Fucus) compared to the oiled sites. The rocks deployed in 1990 were weathered and dislodged from the substrate over the course of the 1990-91 winter at most sites. Many of the rocks had the oil weathered completely from the sampling surface and, consequently, could not be sampled in 1991.

During 1990, the oiled halves of EV and PB rocks had lower densities of barnacle recruits in most cases. Initial settlement (early July) tended to be greater on unoiled halves but differences were only weakly significant (p<=0.18, paired t-Test). There was little recruitment in general later in the season. The freshly coated PB rocks showed greater differences, which were significant over several sample dates at both sites (p>=0.001<0.1, paired t-Test). However, the oil on the PB rocks was washed away in many cases and, by the end of the season with little recruitment occurring, no differences remained. The control rocks cleaned with methylene chloride had no differences in barnacle recruits between treated and untreated sides (0.35=>p<0.9, paired t-Test).

The six tile pairs placed in the field in 1990 had fewer barnacle recruits. Densities were significantly lower (p=0.01, paired t-Test) in early July, and weak significance (p=0.07<0.2, paired t-Test) was found at 6 of 10 sample dates.

There was sparse settlement on the tile pairs placed at control sites in 1991. There were few differences in barnacle recruits, Fucus germlings and percent algal cover and no trends were apparent. However, the two sites (1322X and 1723X) which had good recruitment in 1990 also
had substantial recruitment activity in 1991. The caged tiles of both sites had somewhat greater numbers of barnacles on the unoiled tile compared to the oiled tile except toward the end of the recruitment season, but differences were only weakly significant (p>0.18, paired t-Test). The painted tile pairs had similar levels of barnacle and *Fucus* recruitment on both tiles.

In 1992, barnacle recruitment was substantially lower than in 1991 and patterns were not evident. Data on adult barnacles present on the tiles indicate very few recruits reach adult sizes. *Chthamalus dalli* tended to recruit better on oiled tiles in caged treatments and on unoiled tiles in uncaged treatments, and were not significantly different on painted and unpainted tiles.

In 1991, *Fucus* did not recruit on uncaged or painted tile pairs and only began to recruit on caged, clean tiles at the end of the season. Again in 1992, there was almost no *Fucus* recruitment on uncaged or painted tile pairs. For caged treatments, recruitment tended to be higher on clean tiles with a slight tendency for higher recruitment at control sites.

Recruitment, including that of algal cover, appears to play the major role in structuring invertebrate communities at the Herring Bay study sites. These studies show that oil had an initial effect on barnacle recruitment, and depending upon substrate character, may have a moderate to long-term effect on algal recruitment (Duncan et al., 1992b). Within Herring Bay rock substrate differs from site to site, and several of the study sites have a more porous substrate than others.

For barnacles it is likely that residual tar is an unstable settlement substrate and the reduced densities are a consequence of tar sloughing rather than toxicity. The sites showing the most rapid increases in invertebrate abundance are those most exposed to open water or tidal currents, which probably increases larval availability at those sites. Not surprisingly, these were also the sites hit by the floating oil. Although care was taken in matching rock sizes, the parent material (including the degree of porosity) for each rock) varied greatly. This was especially true with the PB rocks selected. Many rocks were dense and non-porous and the oil quickly dissipated to the extent that comparisons between oiled and non-oiled halves could no longer be made.

The tile pairs were much less variable. Tiles placed in the field in 1990 were of a silicaceous *v. losa* and may have retained north slope crude more effectively than the red clay tiles used in 1991. Nonetheless, all tiles have retained a degree of oil staining not found on many of the rocks.

**References**


The Response Process: The Goals of the Oil Spill Health Task Force
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The day of the Exxon Valdez oil spill had special meaning for the 4,500 Alaska Natives who live on the shores of Prince William Sound and depend upon the sea and shoreline to maintain a subsistence lifestyle. Walter Meganack, the tribal chief of the native village of Port Graham, described the day as “the time when the water died.” He said that the native story was different from the white man’s story.

“Our values are different, how we see the water and the land, the plants and the animals are different. What the white men do for sport and recreation and money, we do for life: for the life of our bodies, for the life of our spirits, and for the life of our ancient culture. The water is sacred.” (Meganack, 1989).

The sea, shoreline and inland areas also provided the majority of protein intake in the diet of Alaskan Natives in the area.

Household surveys conducted by the Subsistence Division of the Department of Fish and Game prior to the oil spill from representative Prince William Sound villages documented up to 300 pounds of protein per person per year came from wild meat, fish and fowl (ADF&G, 1984). By comparison the comparable amount of the above food purchased in the Western U. S. is 220 lb.

The Oil Spill Health Task force was formed initially in April 1989 to respond in as timely and informative way as possible to the public’s inquiry about the short and long term safety of subsistence food exposed to Exxon Valdez oil. The collective knowledge of the initial group of members (Indian Health Service, State Division of Epidemiology, Subsistence Division of the Alaska Department of Fish and Game, The North Pacific Rim Native Corporation and the Kodiak Area Native Association) on the toxicology of oil and subsistence food was nonexistent.

Calls for federal assistance were not answered. The reason for the lack of response soon became clear. In a review of the world literature on behalf of the Oil Spill Task Force, toxicologist Dr. Gary Winston of Louisiana State University found “a virtual absence of literature which investigated any human health effects, concerns or implications as a function of oil spills other than those which were related directly to primary exposure to clean up crews.” (Winston, 1990). Further inquiry to the Food and Drug Administration revealed no established safety levels for hydrocarbons for food.

The Task Force (joined in the late summer of 1989 by representatives from NOAA, the Toxicology Division of the Exxon Corporation and the Alaska Department of Environmental Conservation) developed the following mission: obtain as much historical information as possible about health effects of crude oil by both direct exposure and exposure through the food chain, conduct studies of subsistence foods for contamination with oil, interpret the results of these studies, and disseminate this information to the public.

As sample data on hydrocarbon concentrations in subsistence foods became available, expert advice was needed to interpret the results. Through NOAA’s
help the task force was able to gather a group of nationally known senior toxicologists and scientists in what has become known as the Oil Spill Expert Toxicology Committee (Shank, 1990). Their recommendations formed the basis of our communication to the public.

At our request the FDA did a quantitative health risk assessment of subsistence food exposed to Exxon Valdez oil, and in August 1990 we received an advisory opinion of the safety of aromatic hydrocarbon residues found in subsistence foods most important to Alaskan Natives.

This then is the background to the monumental effort that ensued to insure food safety and the efforts of the Task Force to communicate this information to subsistence users in the numerous villages in the oil spill area.

References


Subsistence Uses of Fish and Wildlife Resources in Areas Affected by the Exxon Valdez Oil Spill
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This paper discusses changes in subsistence uses of fish and wildlife resources in 15 predominantly Alaska Native communities whose hunting, fishing, and gathering areas were affected by the Exxon Valdez Oil Spill. It is based upon research conducted by the Division of Subsistence of the Alaska Department of Fish and Game. Study communities include 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.

Prior to the spill, the division had conducted baseline research in all 15 villages. These studies found that subsistence harvests in these communities in the 1980s were large and diverse, 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 researchers interviewed representatives of 403 households in these 15 communities. Study findings revealed that after the spill, subsistence harvests declined markedly 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.

Very similar changes were documented for English Bay and Port Graham. Compared to 1987, harvest quantities were down 51 percent at English Bay and 47 percent at Port Graham. The range of resources used per household dropped at English Bay from an average of 25.0 kinds in 1987 to 13.7 kinds in 1989. At Port Graham, the household average was 21.5 in 1987 and 11.2 in 1989.

Subsistence harvests in all six Kodiak
area villages also declined in 1989 compared to pre-spill averages, although a wider range of changes was documented. Harvests as measured in pounds per person per year were down 77 percent in Ouzinkie, 60 percent in Karluk, 52 percent in Port Lions, 40 percent in Old Harbor, 31 percent in Larsen Bay, and 12 percent in Akhiok.

In contrast, subsistence harvests in the five Alaska Peninsula communities showed little change, or increased, in 1989 compared to 1984, the only pre-spill year for which comprehensive data are available. Household interviews revealed that the presence of sheen, mousse, and tar balls temporarily disrupted subsistence harvests near these communities. However, most families resumed subsistence activities within several months. Resource use diversity also remained very high in the Alaska Peninsula villages, ranging from 15.3 resources per household in Chignik Lagoon to 29.7 kinds per household in Ivanof Bay.

When asked to provide reasons for declines in subsistence harvests in the year following the spill, 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.

Regarding contamination concerns, it should be noted that little specific information was available to subsistence harvesters concerning the safety of using subsistence resources from the spill area until September 1989, by which time spring, summer, and most fall harvest opportunities had passed. Complete information from tests of fish and shellfish from subsistence foods testing programs were not available until February 1990, and information about marine mammals, birds, and deer was not available until June 1990. Interviews conducted in 1990 found that many households continued to express doubts about subsistence food safety. Respondents cited the relatively small number of samples tested in 1989, the limited sites examined, and the limited range of species tested as some reasons for their continuing questions. Also, hunters and fishermen continued to observe the presence of oil in harvest areas as well as dead and damaged wildlife which they attributed to the spill. Such signs were understood as evidence of continuing danger and many households thus acted cautiously with respect to using subsistence foods. Such behavior is culturally consistent for people whose survival has long relied upon their observations of the natural environment.

In 1991, the division 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 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 Tattlek. 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 Tattlek, 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 Tattlek 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 during 1990-1991.
Overview of Subsistence Food Safety Testing Program

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The Oil Spill Health Task Force, a group chaired by a Public Health Service physician and composed of representatives from state and Federal agencies, native organizations, and Exxon, was formed soon after the Exxon Valdez oil spill to address public health concerns resulting from the spill. The Oil Spill Health Task Force served as a forum for design of the subsistence food safety testing study and the communication of the results and conclusions derived from the study to the subsistence communities.

The main objectives of the study were to determine if subsistence foods were contaminated as a result of the spill and to assess the implications for subsistence food safety. In order to put together a comprehensive study, NOAA and Exxon signed a Memorandum of Understanding in the summer of 1989 which had three principal features: (1) NOAA biologists would accompany Exxon-sponsored collection teams to the villages and participate in the sample collections; (2) tissue samples from fish and shellfish subsistence resources would be analyzed for aromatic contaminants by the NOAA National Marine Fisheries Service Environmental Conservation Division laboratory in Seattle; and, (3) all data from the study would be made public.

These steps were taken to ensure that there were no questions about the validity of the data produced by the study and that the results and the implications for human health were made available to public health officials and the communities in a timely manner.

This paper addresses the general sampling strategy, the numbers and types of samples collected, the identification of the most contaminated sites, and issues related to the interpretation of the shellfish results. Subsequent papers in this session will address in more detail the results from chemical analysis of shellfish, fish, and marine mammal tissues, the implications of those results for human health, and an evaluation of the methods used in risk communication.

The study area included subsistence seafood collection areas in Prince William Sound (Tatitlek and Chenega Bay); Lower Cook Inlet (including the Outer Kenai Peninsula villages of Port Graham and English Bay, and Windy Bay); and Kodiak Island (Kodiak City, Chiniak, Larsen Bay, Karluk, Akhiok, Old Harbor, Ouzinkie, and Port Lions). Four subsistence areas on the Alaska Peninsula (Chignik, Perryville, Ivanof Bay, and Kashvik Bay) were sampled by ADF&G in 1990. Reference samples were collected from near the village of Angoon in 1989 and Yakutat in 1990. The initial sampling plan called for approximately equal numbers of samples from each village area, although there were considerable differences in the potential degree of impact from the Exxon Valdez oil. Sampling sites that represented important subsistence use areas were selected in consultation with village representatives. The degree of oiling was not a major factor in site selection. Two important subsistence beaches for the collection of intertidal shellfish were identified in each
village area. Target species included several species of intertidal shellfish (mussels, clams, chitons), bottomfish (primarily halibut), and salmon. Other species were also collected but in much smaller numbers. Intertidal stations for the collection of shellfish did not represent exact locations on a given beach. Thus, several species (e.g., mussels, clams, and chitons) were often collected from the same station, although each species occupied a different habitat (tidal elevation, substrate) in the beach.

In 1990, the number of sample stations and the number of samples per station were increased. In 1991, only shellfish were collected. The focus in 1991 was in southwestern Prince William Sound near Chenega Bay, because that part of the Sound had potentially the greatest amount of oiled shoreline, and Windy Bay, because that was the most heavily-oiled site sampled and was a good site to examine changes in concentration over time. Both Exxon and the Alaska Department of Fish and Game sponsored sample collections and analyses in 1990 and 1991.

A total of over 1,000 shellfish samples collected from more than 65 stations were analyzed for aromatic contaminants in three years of sample collections. Five stations had one or more shellfish samples with total aromatic contaminant concentrations exceeding 1 ppm (part per million): two stations in Prince William Sound (one in Port Ashton in Sawmill Bay near the village of Chenega Bay and the other on southwestern Eirlington Island); two islands in Windy Bay on the Outer Kenai Peninsula; and a station on Near Island, near the Kodiak boat harbor. The Windy Bay stations and the Eirlington Island station both had obvious visual evidence of oiling.

At the most contaminated station, an island in Windy Bay, total aromatic contaminant concentrations in mussels varied by as much as three orders of magnitude from the same collection period over a relatively small beach area. The highest concentrations were found in mussels collected at a location higher in the intertidal area.
Assessment of Exposure of Subsistence Fish Species to Aromatic Compounds Following the Exxon Valdez Oil Spill

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On March 24, 1989, the Exxon Valdez ran aground on Bligh Reef spilling Prudhoe Bay crude oil (PBCO) into Prince William Sound, a relatively pristine area in Alaska. The oil spread through the Sound and into coastal areas along the Gulf of Alaska, affecting fishing grounds used by Alaska Native villages. The Alaska Natives were concerned about possible contamination by the spilled petroleum of fish and shellfish used for subsistence.

In response to this concern the National Oceanic and Atmospheric Administration (NOAA) entered into an agreement with the Exxon Corporation and the Alaska Department of Fish and Game (ADF&G) to survey native subsistence fisheries for exposure of fish and shellfish to oil. Here, we present the results from chemical analyses of several species of salmon and bottomfish collected from a number of fishing grounds used by native villagers to assess the extent of exposure of fish to spilled oil and the accumulation of petroleum-related compounds in edible flesh.

Of particular concern was the accumulation of aromatic compounds (ACs) present in oil, because some of these ACs are suspected of being toxic to humans (Dipple et al., 1984). The ACs measured included polycyclic aromatic hydrocarbons and sulfur-containing ACs. Additionally, several of the ACs (e.g., alkylated naphthalenes, phenanthrenes and dibenzothiophenes) measured were characteristic of oil and particularly PBCO (Krahn et al., 1992). The results from the analyses of edible flesh of fish, in addition to results from the analysis of shellfish (Brown et al., this volume), were then evaluated by the Alaska Oil Spill Health Task Force and the U.S. Food and Drug Administration (FDA) to assess the potential risk to Alaska Natives of eating seafood from their traditional fishing sites following the spill.

Previous studies (Varanasi et al., 1989) have shown that fish have the capacity to biotransform many ACs to polar metabolites that are readily excreted into bile, which is retained in the gall bladder. Moreover, these studies showed that the extensive biotransformation of ACs by fish greatly limits the accumulation of these compounds or their metabolites in edible tissues. Accordingly, a rapid and sensitive semiquantitative method (Krahn et al., 1986) for measuring concentrations of fluorescent aromatic compounds (FACs) in bile was used to estimate exposure of fish to ACs that are present in oil. These results were then used for prioritization of edible flesh samples for a more extensive analysis of the presence of parent ACs by gas chromatography/mass spectrometry (GC/MS).

Concentrations of FACs in the bile of five species of bottomfish and five species of salmon collected from oil-impacted sites located in Prince William Sound and along the Gulf of Alaska were
determined. Elevated concentrations of FACs in bile of fish from several sites indicated exposure to ACs. For example, in 1989, mean concentrations of FACs were highest in bile of both salmon and bottomfish from sites near Chenega Bay (6000 ± 3400 and 5100 ± 4000 ng phenanthrene equivalents per mg bile protein, respectively) and Kodiak (2800 ± 1900 and 7550 ng phenanthrene equivalents per mg bile protein, respectively), which were heavily impacted by spilled oil. Moreover, these concentrations were substantially higher than the concentrations in salmon (1100 ± 2200 ng phenanthrene equivalents per mg bile protein) and bottomfish (310 ± 120 ng phenanthrene equivalents per mg bile protein) from Angoon, a reference site.

In the following year, salmon and bottomfish from Chenega Bay showed marked decreases in biliary FAC concentrations (550 ± 250 and 1300 ± 850 ng phenanthrene equivalents per mg bile protein, respectively) suggesting that the level of exposure to ACs in salmon from the Chenega Bay site had declined. Interestingly, no temporal changes were evident in salmon sampled from sites near Kodiak in 1990 (no bottomfish were sampled from this site). The concentration (2400±2000 ng phenanthrene equivalents per mg bile protein) of FACs in salmon from Kodiak was comparable to the concentration in 1989 indicating that exposure to ACs was unchanged for salmon captured at this site. These results and data from analyses of shellfish from Kodiak (Brown et al., this volume) suggest exposure to a source of ACs other than spilled oil.

The HPLC analysis of bile for FACs provides a rapid, semiquantitative assessment of exposure to ACs that are present in oil but does not allow identification of individual compounds found in bile. In a related study (Krahn et al., 1992) conducted as part of the Natural Resources Damage Assessment effort, it was shown that the bile method is a sensitive indicator of exposure of fish to specific ACs present in oil. In the study of Krahn et al. (1992), metabolites of ACs characteristic of PCBs were identified, by GC/MS, in high proportions in bile of fish injected with PCBs and in fish sampled from sites in Prince William Sound shortly after the spill. Metabolites of these ACs were not present in bile of fish sampled from a reference site distant from the spill. These findings substantiated the use of the bile method to rapidly assess exposure of fish to ACs in the present study.

As mentioned, the major use of the results on concentrations of biliary FACs was to prioritize corresponding edible flesh samples for more extensive analysis of the presence of parent ACs by GC/MS. Samples showing a range in exposure to oil were chosen for comprehensive analysis to determine if fish were accumulating significant levels of parent ACs in their edible tissue and to substantiate that low concentrations of FACs in bile accurately reflect minimal exposure to ACs and, hence, little potential for accumulation of ACs in muscle tissue.

The concentrations of biliary FACs in fish from which samples of muscle tissue were analyzed for parent ACs ranged from 10 to 18,000 ng phenanthrene equivalents per mg bile protein. In contrast, concentrations of total ACs (sum of individual selected ACs) analyzed by GC/MS in corresponding muscle tissue were low. No appreciable concentrations (<1 ng/g wet weight [ppb]) of parent ACs were detected in muscle of
bottomfish, and although concentrations of ACs in muscle of salmon were somewhat higher they very rarely exceeded 100 ppb, and in the majority of samples the concentrations of ACs were less than 30 ppb.

These findings showed that exposure of salmon and bottomfish to ACs does not lead to any significant accumulation of parent ACs in edible muscle tissue. These results also corroborate findings from laboratory studies on the pathways of metabolism and disposition of ACs in fish, showing that polar metabolites of ACs accumulate in bile and that parent ACs do not accumulate to significant concentrations in muscle tissue (Stein et al., 1987; Varanasi et al., 1989). The consistency of the results from this field study and those of previous laboratory studies provided evidence of minimal risk of exposure of humans to parent ACs from consumption of edible flesh of fish captured at sites impacted by the spilled oil.

The extensive biotransformation by fish of ACs to polar metabolites raised the issue of whether metabolites were present at elevated concentrations in muscle tissue of fish exposed to ACs. Accordingly, a method similar to the bile screening method is being developed (Krone et al. 1992) to estimate concentrations of AC metabolites in fish tissues. This new method has not been validated as extensively as the bile method, thus the results must be considered preliminary. However, analysis of a few selected samples of muscle from salmon indicated that concentrations of AC metabolites were also quite low. This finding is consistent with previous laboratory studies (Stein et al. 1984) with ACs that showed metabolites of ACs as well as parent compounds are low in muscle of fish, and demonstrates the importance of laboratory studies, which lead to the development of techniques that provide the necessary information to respond effectively to environmental emergencies.

In summary, the results of this survey of Alaska Native subsistence seafood provided substantial evidence that fish were exposed to ACs that appeared to originate, in most cases, from the spilled oil. However, edible muscle tissue in salmon and bottomfish were found to have concentrations of ACs that rarely exceeded the relatively low concentration of 30 ppb. These data showing low concentrations of parent ACs in muscle of fish exhibiting a substantial range in exposure to ACs were used by the Alaska Oil Spill Health Task Force and the FDA in arriving at an advisory position that consumption of the flesh of fish posed minimal risk to native Alaskans.

References


Petroleum Hydrocarbons in Alaskan Invertebrate Subsistence Foods Following the 1989 Exxon Valdez Oil Spill


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The Exxon Valdez ran aground on Bligh Reef, Prince William Sound, Alaska on 24 March, 1989, spilling millions of gallons of Prudhoe Bay crude oil (PBCO). During the weeks following the spill, large amounts of oil flowed toward southwestern Prince William Sound, and as a result, many shorelines were oiled. The spreading of spilled oil raised many concerns, and among them was the concern that subsistence seafoods (e.g., fish and invertebrates) were contaminated (see abstracts by J. Field and J. Stein et al.) by the spilled petroleum.

The objectives of this paper are to describe the extent and duration of contamination of invertebrates by the spilled oil. The data from this study together with those described by Stein et al. (in this session) were used by the Alaskan Oil Spill Health Task Force and the U.S. Food and Drug Administration to address the issue of potential risk to native Alaskans of eating seafood from their traditional collection sites.

Crude petroleum contains many hundreds of individual chemicals which are generally divided into classes such as aliphatic hydrocarbons, aromatic hydrocarbons and other constituents containing sulfur, oxygen and nitrogen (Clark and Brown, 1977). Among these compounds are dibenzothiophene and alkyl-substituted dibenzothiophenes, which are significant components of PBCO and can serve as useful markers in discerning PBCO. Among the constituents of petroleum, the aromatic hydrocarbons are considered the most toxic. The lower molecular weight aromatic compounds (LACs), those that contain three or fewer benzene rings, have been found to be the more acutely toxic, whereas the higher molecular weight aromatic compounds (four to six rings, HACs) are generally considered the more chronically toxic components.

A majority (99%) of the ACs in fresh PBCO measured in this study consisted of LACs. However, as the oil weathered, the concentrations of many of the more volatile and water soluble LACs decreased rapidly. Sixteen non-substituted ACs and 17 groups of alkyl-substituted ACs comprising some 270 individual chemicals present in PBCO were determined in subsistence seafood samples to assess the extent of contamination, to evaluate temporal changes, and to compare to possible sources.

More than a thousand samples of fish, marine mammals, and invertebrates were collected between 1989 and 1991 and were analyzed for ACs by gas chromatography/mass spectrometry according to Krahn et al. (1988). These samples included a variety of invertebrates from 80 sampling stations used by the residents of 17 villages for collecting subsistence seafoods. The focus of this paper will be on the four target invertebrate taxa; mussels (*Mytilus edulis*), butter clams...
(Saxidomus giganteus), littleneck clams (Protothaca staminea), and chitons (order Neoloricata).

For discussion purposes, invertebrate samples (wet weight basis) are divided into four categories on the basis of the sum of concentrations of the ACs:

1. Not contaminated - <10 ng/g;
2. Minimally contaminated - from 10 ng/g to 100 ng/g;
3. Moderately contaminated - from 100 ng/g to 1000 ng/g;
4. Heavily contaminated - >1000 ng/g.

Invertebrates from most of the 17 villages and the two reference areas, Angoon and Yakutat, fell into the first two categories: not contaminated or minimally contaminated. Invertebrates from some stations at two sampling areas, Chenega Bay and Windy Bay, and from two stations near Kodiak Island were moderately or heavily contaminated with ACs.

Following the spill, oil was observed in Chenega Bay in the vicinity of station CHE1 (the beach below the village of Chenega Bay—used by villagers as a harvesting area). A tar mat about 1 m wide extended the length of the beach at the high tide line at CHE10 (the southern end of Erinlington Island). Invertebrates from eight of eleven stations at Chenega Bay were not contaminated or were minimally contaminated. Invertebrates from three stations at Chenega Bay from one or more sampling events were moderately or heavily contaminated. Specifically, the mussels collected from CHE1 (1989) and CHE7 (at Port Ashton-1990) were moderately contaminated and those from CHE10 (1990) were heavily contaminated.

However, mussel samples collected from CHE1 in 1990 and 1991, and mussels collected from CHE7 and CHE10 in 1991 were minimally contaminated. Butter clams collected from CHE7 (1990 and 1991) and littleneck clams collected in 1990 were moderately contaminated. Butter clams from CHE1 (1989, 1990, and 1991) and from CHE10 (1990) were minimally contaminated as were littleneck clams from CHE1 (1990 and 1991) and from CHE10 (1990, 1991). Butter clams from CHE10 (1991) and chitons from several stations were not contaminated.

Based on mean concentrations of ACs, invertebrate samples from two of the five stations sampled at Windy Bay (stations WNB4 and WNB5) were not contaminated or were minimally contaminated. Two stations, WNB1 and WNB3, located on two adjacent small islands in the mouth of Windy Bay, were both observed to be moderately to heavily oiled.

The degree of contamination of invertebrates from these two stations varied with sampling year and by species. Specifically, mussels from Windy Bay station WNB1 (1989) and from WNB3 (1990) were heavily contaminated, whereas the concentrations of ACs in mussels from these stations in 1991 were much lower (minimally to moderately contaminated).

Mussels were not collected at WNB1 in 1990 or at WNB3 in 1989. Only one sample was collected at WNB2, littleneck clams sampled in 1989, which were almost in the heavily contaminated category, with 960 ng/g ACs.

Invertebrate samples from two sampling stations on Kodiak Island (KOD3 and OHA4) also contained elevated concentrations of ACs. Station KOD3 was located near the city of Kodiak and adjacent to the boat harbor. An oily sheen was observed on one occasion at KOD3 by the field party while digging for clams. Mussels, butter clams, littleneck clams, and chitons from station KOD3 from both
1989 and 1990 were moderately or heavily contaminated.

Station OHA4 at the village of Old Harbor was also near a boat harbor. Oil was not observed to be present during sample collection at this site. Butter clams and littleneck clams collected at Old Harbor station OHA4 in 1989 and mussels collected in 1990 were just within the moderately contaminated category. Five of the six mussel samples and three of six butter clams (collected in 1989) were minimally contaminated.

The relative amounts of the ACs can be useful in evaluating temporal changes and to compare to potential sources. The relative amounts of the parent and alkyl-substituted ACs are useful for comparing patterns of these ACs among petroleums, petroleum products, related materials, and ACs in invertebrate samples. Dibenzothiophene and alkyl-substituted dibenzothiophenes (which comprise 27 discernible components in PBCO) were particularly useful in making comparisons.

For example, these chemicals were mostly absent in a sample of Cook Inlet crude oil but were much more prominent in a sample of Kuwaiti crude oil than PBCO. Graphs of these patterns from various oils and from certain moderately and highly contaminated invertebrate samples were compared and the same data were treated using principal components analysis and hierarchical cluster analysis. The relative amounts of these analytes in oil collected nine days after the Exxon Valdez spill were similar to those in the fresh oil except for a loss of the more volatile and water soluble components, particularly, naphthalene, C1- and C2-naphthalenes.

The pattern of ACs in a sample of oil collected from the beach at Snug Harbor 15 months after the spill was similar to that of the nine-day weathered oil. The patterns of ACs in mussels from Windy Bay station WNB3 collected in 1989 were similar to the oil sample from Snug Harbor except for additional losses of the more volatile and water soluble components of LACs. The temporal changes of the patterns of ACs in mussels collected from Windy Bay from 1989 to 1991 showed increasing losses of the more volatile and water soluble components of LACs. Evaluation of the patterns of ACs from mussel samples from CHE7 implies the presence of PBCO plus ACs indicative of combustion products.

ACs present in samples from Kodiak Island stations OHA4 and KOD3 were indicative of petroleum or petroleum products and the pattern of ACs was very similar to that of the nine day weathered PBCO. The pattern of the ACs in a mussel sample from KOD3 was essentially the same as in butter clams from the same site collected in March 1990, April 1990, and September 1990, and in a littleneck clam sample collected April 1990 at KOD3. There was little evidence of temporal change in the pattern of ACs in these clam samples from KOD3 which could imply a continual exposure to the same source of ACs. It is possible that there is a local and continual source of hydrocarbons in the area of these two stations that would have a pattern of ACs similar to the somewhat weathered PBCO.

In summary, invertebrate samples from most stations, including those from the two reference areas, were not contaminated or were only minimally contaminated with ACs typical of petroleum. Invertebrates from a few stations in the Chenega Bay sampling area and Windy Bay were moderately or heavily
contaminated with ACs. Invertebrates from one station (KOD3) on Kodiak Island were moderately to heavily contaminated with ACs and the concentrations did not appear to decrease significantly from 1989 to 1990 (samples were not collected in 1991) suggesting the presence of other possible sources of ACs not related to the Exxon Valdez spill. Mean concentrations of ACs in mussels from the more contaminated sites at Chenega Bay and Windy Bay generally decreased with time. However, because of sample variability, it is difficult to draw conclusions about temporal trends.

References

Investigations of Crude Oil Contamination in Intertidal Archaeological Sites Around the Gulf of Alaska

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The State of Alaska initiated a brief study during 1991 aimed at investigating the presence of crude oil in archaeological sites which occur in the intertidal zone. The concern was that cultural deposits subjected to oiling retained crude oil contaminants that would affect radiocarbon dates obtained from the sites. Designed to complement a larger, area-wide study funded through the U.S. Forest Service, the State study concentrated on 13 intertidal sites suspected to contain intact cultural deposits. Site selection was based on documented presence of cultural remains in the intertidal zone and evidence of beach oiling during the Exxon Valdez oil spill. Preliminary field examinations eliminated 10 sites from further examination because they lacked intact cultural deposits. One site above the high tide line was added to test presence of wind or storm wave-borne oil contaminants.

Laboratory studies about the effect of incorporation of crude oil on radiocarbon dating with datable samples suggested that significant skewing of dates occurred (Mifflin and Associates, 1991). The goals of the project therefore were to test the selected sites for presence of oil and to concurrently test the reliability of radiocarbon dates from the deposits. Comparison of time diagnostic artifacts from the tested sites with similar artifacts from well dated nearby sites was the method chosen to check validity of the oiled site dates. Sites were partially excavated to obtain large enough collections and adequate radiocarbon samples to accomplish the comparison.

Sites were tested to reveal stratigraphy of deposits in the middle to upper intertidal zone and sediment samples collected to test for presence of subsurface oil. Selected sediment samples were submitted to the National Oceanic and Atmospheric Administration/National Marine Fisheries Service laboratory in Seattle for analysis by high performance liquid chromatography with ultraviolet detection (HPLC/UV). One sample from the AFG-098 Site on Shuyak Island and a sample from the SEL-215 Site on Nuka Island contained minute traces of petroleum hydrocarbons.

The AFG-098 Site on Shuyak Island contains cultural deposits which yielded artifact collections typical of Koniag Phase from the region and provides the best opportunity to test the hypothesis that contamination affected radiocarbon dating. Two cultural levels are clearly separate in the stratigraphic profile of the site. The Lower Component is an early Koniag Phase collection containing stemmed, ground slate, projectile points with barbs. Cross-section of the points is generally a flattened biconvex form although some points have a medial ridge on one face. Another form of point, triangular in outline with a flat basal facet, was found in the lower level of the site. Ground slate ulus from the component have straight, bifacially ground cut-
ting edges. The collection contains planing adzes of the variety usually inset into a bone socket and then hafted. Other diagnostic artifacts in the Lower Component include a slate fragment with an etched face, a stone saw, and chipped slate preforms for subsequent grinding into projectile points.

Similar, early Koniag Phase collections at well dated sites in the region have assigned ages of between A.D. 1350 and A.D. 1500. Age estimates for the Koniag Phase in the Kodiak Archipelago cite a beginning around A.D. 1100 to A.D. 1200. Age of the incised slate figurines or faces is particularly well defined during the A.D. 1350 to A.D. 1500 period. Triangular ground slate points with a flat ground basal facet typically date from A.D. 1300 to A.D. 1500. Four radiocarbon samples stratigraphically associated with the Lower Component range from A.D. 787 ±110 to A.D. 1143 ±65. The four dates are acceptably within the earliest estimated range of the Koniag Phase and may indicate that the developmental stage of the phase occurred earliest in the northern Kodiak area.

The AFG-098 Upper Component collection provided an artifact collection which is clearly related to Koniag Phase materials elsewhere. Ground slate projectile points of several forms were recovered. Stemmed points, some with barbs and some with rounded shoulders, were the most common forms recovered. Medial ridges were present on some barbed forms but a flattened biconvex cross-section was most common among the stemmed points. A very distinctive ground slate projectile point with a triangular outline and a sharply defined flute or butt facet was found in the Upper Component. Several ground slate ulu forms occur in the component. Both are bifacially ground and have straight to slightly convex cutting edges. One form has a distinctive notch or offset at the back of the blade which suggests hafting at the back edge near one end with the other end extending out of the handle. Other stone artifacts from the Upper Component include a stone saw, sawn slate fragments, whetstones, planing adzes, a quartz crystal, a hematite nodule for rehafting, and chipped slate preforms. Fragments of several bone or ivory dart heads with unilateral barbs, a barbed hook fragment, and bone awls are some of the organic artifacts recovered. A small jet labret was also found. Fragile artifacts carved from spruce wood, bark and grass matting, and fragments of a birch bark container were recovered from the saturated deposits. More than a dozen species of seeds were found in floor deposits of the Upper Component.

Comparison of the Upper Component collection with Koniag Phase or related site collections on Kodiak Island, both sides of the Alaska Peninsula, and the outer coast of the Kenai Peninsula demonstrate close similarities. The triangular point form with a basal flute consistently occurs in Koniag Phase or related collections dating from between A.D. 1500 and Historic times (A.D. 1750-1800). Other point and ulu forms are consistent with later Koniag Phase ages as well. Six radiocarbon dates obtained from the Upper Component levels of AFG-098 range from A.D. 1343 ±60 to A.D. 1490 ±125.

The AFG-082 Site is an upland site eroding slowly into the intertidal zone which was tested for contamination from storm wave or wind deposited oil. The ground slate ulus, chipped bifaces, planing adze, and small single chamber
houses compare reasonably well with middle age range Kachemak Tradition remains, approximately 2,000 years old. The ratio of ground slate to chipped stone remains also supports a Kachemak Tradition comparison. Unfortunately, the AFG-082 collection is too small and typologically limited to provide a very accurate age estimate.

Two radiocarbon samples obtained from the site date to A.D. 203 ±65 and A.D. 288 ±65. The AFG-082 dates fall well within the expected age range determined from artifact typology. No evidence of oil was found in the site and no sediment samples were submitted for analysis.

The SEI-215 Site on Nuka Island contains intact cultural remains within a peat deposit in the intertidal zone. Time specific traits in the collection are meager but grooved splitting adzes suggest an age between A.D. 1000 and A.D. 1500. Inclusion of a glass trade bead in the collection is interpreted as an intrusive historic element.

Radiocarbon samples from the site yielded seven dates ranging from A.D. 1142 ±60 to A.D. 1442 ±105. A trace of oil was detected in one of the two sediment samples submitted for HPLV/UV screening. However, the radiocarbon determinations compare well with the expected age of the deposits.

The SEW-068 Site consists of a peaty intertidal deposit containing cultural remains which relate to Kachemak Tradition collections elsewhere. Grooved splitting adzes located nearby may not be associated however such tools have been dated to that early time from other sites in Prince William Sound. A general estimate of age for the peaty deposits, based on artifact typology, is 1000-2000 years ago. Geological age estimates based on rates of isostatic rebound from the 1964 Earthquake and from long term regional subsidence indicate the deposits should be at least 1500 years old. Two wood samples from the saturated deposits provided radiocarbon dates of A.D. 10 ±65 and A.D. 391 ±65. The ages obtained from the culturally modified wood fragments agree roughly with the expected age of the cultural deposits.

Conclusions drawn from this study include:

1. Intertidal archaeological deposits at three of the sites investigated demonstrate that useful and important information is preserved in some intertidal sites even though there is sometimes no surface evidence of buried remains.
2. Traces of petroleum hydrocarbons in subsurface remains do occur although the origin of the contaminants in the sites tested is unknown.
3. Reliable radiocarbon dates can be obtained from oiled deposits. It is uncertain, however, whether that results in the tested sites from cleaning of the samples or simply lack of actual contamination. Examination of samples in the radiocarbon laboratory for oil contaminants should be routine and cleaning methods should be modified if necessary to remove identified contaminants.
4. Dating of intertidal or even exposed upland archaeological remains needs to involve every possible approach to dating, not just reliance on a single method. Archaeologists investigating chronological questions in the area of the Exxon Valdez oil spill need to be especially critical with their conclusions. No evidence was found in the sites examined that the Exxon Valdez
oil spill adversely affected the radiocarbon dating results. Damage to sites appears to be from erosion or vandalism rather than direct oiling.

References
Generating Damage Restoration Costs for Archaeological Injuries of the Exxon Valdez Oil Spill
Martin E. McAllister
Archaeological Resource Investigations

This paper summarizes the results of a monetary assessment of damage for injuries to archaeological sites documented in the Exxon Valdez oil spill response records. Injuries attributable to the oil spill at 35 archaeological sites in Prince William Sound and the Gulf of Alaska were analyzed to estimate restoration costs for use by the Exxon Valdez Trustee Council in planning restoration of damages for archaeological resources. The damage assessment was accomplished in two steps.

First, a damage assessment panel, chaired by the author, met to consider restoration costs based on the archaeological injury data. Second, working from the findings of the panel, additional analyses were conducted by the author to calculate specific restoration costs for the archaeological injuries. Two levels of restoration costs were produced by the damage assessment process. First, site-specific restoration costs were developed for the archaeological sites identified as having substantive injuries. Second, gross restoration costs were estimated for projected numbers of sites injured by the oil spill.

The procedures employed by the damage assessment panel were carried out in nine steps:

1. The data on the 35 archaeological sites with injuries attributable to the oil spill and other relevant data sources were reviewed.
2. A conceptual framework on which restoration costs would be based was developed from the damage assessment model contained in the Archaeological Resources Protection Act of 1979, as amended (ARPA).
3. Documented oil spill injuries to archaeological sites were analyzed and grouped into two major categories, those resulting from oiling and those resulting from oil spill response activities.
4. Two restoration options were developed, one for ten years of oil effect monitoring and one for direct physical restoration. These were used to formulate specific restoration measures appropriate for the two categories of injuries.
5. Ten injured sites were eliminated from further consideration because appropriate site restoration work had already been accomplished or the site damage was not severe enough to require restoration. Damage at one site was determined to be unrestorable.
6. Three categories of site-specific restoration proposals were developed for the remaining 24 sites: sites recommended for monitoring only, sites recommended for direct physical restoration only, and sites with both types of measures recommended.
7. Standard levels of effort were formulated for direct physical restoration in year one and in years two through ten for oil effect monitoring. Appropriate site-specific salary estimates
were generated using standard levels of effort as a guide.

8. Site-specific support costs necessary to carry out direct physical restoration measures and oil effect monitoring were estimated.

9. Restoration costs were estimated for four different injury scenarios, each with a different number of injured sites, using average per site costs for direct physical restoration measures and oil-effect monitoring.

Two principal sets of findings were produced. The first consists of the proposals for site restoration measures and costs for the 24 archaeological sites with substantive injuries. The second consists of restoration costs for projected numbers of sites injured by the oil spill.

Site-specific restoration proposals are based on the oil effect monitoring and direct physical restoration measures. Using the above criteria, there are five sites in the oil effect monitoring only category, 14 sites in the direct physical restoration only category, and five sites at which both types of measures are recommended.

The first element of the restoration cost proposals for the 24 sites are personnel salaries. The salary figures for 17 of the 24 sites are based on the three standard levels of effort defined above. Due to special circumstances, seven sites have salary figures based on variations of the standard computations.

Five sites have cost proposals involving only salaries for ten years of monitoring. The standard salary figure for year one oil effect monitoring is $2,904.51, and $2,202.17 per year for years two through ten or $19,819.53 for 9 years. Therefore, the total salary figure for each of these sites is $22,724.04.

Salary for direct physical restoration only is proposed for 11 sites. The total salary figure for each of these sites is $3,155.79.

Only one site is in the oil effect monitoring and direct physical restoration salary category. The total salary figure for this site consists of the standard salaries for ten years oil-effect monitoring, plus costs for direct physical restoration—$25,879.83.

Four sites have salary figures for direct physical restoration measures above the standard level of effort, as well as oil effect monitoring. One has disinterred human remains which required the addition of eight days of project supervisor time for consultation with Native Corporations. The result is a salary increase of $1,804.24 over the standard salary for direct physical restoration. The total salary figure for the site consists of the amount for the combined standard salaries shown in the preceding paragraph and the extra cost for consultation, $25,879.83 + $1,804.24, or $27,684.07. At the other three sites, a test excavation is proposed to fully assess the magnitude of damage. This required the addition of two person days for fieldwork and one person day each for analysis and report preparation. The result is a salary increase of $527.76 over the standard salary for direct physical restoration. The total salary figure for these sites consists of the amount for the combined standard salaries and the extra cost for the test excavation, $25,879.83 + $527.76, or $26,407.59.

One other site is proposed for direct physical restoration salary above the standard level, but not for oil effect monitoring. Because this site has disinterred human remains, eight days of project supervisor time were added for consultation with Native Corporations at the
cost of $1,804.24. Also, the large volume of disturbance at this site required the addition of four person days for fieldwork and two person days each for analysis and report preparation. The result is a salary increase of $1,055.52 over the standard salary for direct physical restoration. The total salary figure for this site consists of the standard salary for direct physical restoration and the extra costs for consultation and restoration measures, $3,155.79 + $1,804.24 + $1,055.52, or $6,015.55.

Finally, two sites in the direct physical restoration only category have salary figures below the standard level because their injuries require measures different from those proposed for most other sites. For one site, the total salary figure of $2,480.83 is for repatriation or reinterment administration and consultation. The direct physical restoration measures proposed for the other site allowed the elimination of two person days for fieldwork and one person day each for analysis and report preparation. The result is a salary decrease of $892.08 from the standard salary for direct physical restoration to a total salary figure of $2,263.71.

The other elements of the restoration cost proposals are support costs. Basic support costs are for: fieldwork per diem, transportation, supplies and equipment, and processing and duplication. Recovery of items requiring expenditures for curation is anticipated at all but two of the sites proposed for direct physical restoration measures. The proposals for three sites involve repatriation or reinterment costs. (At one site, the only support costs are for repatriation or reinterment.)

The support cost amounts vary by site. The average support cost figures are: for year one oil effect monitoring, $4,086.83; for years two through ten oil effect monitoring, $33,183.60; and for direct physical restoration, $10,920.33.

The total figures for the restoration cost proposals for the 24 sites under consideration are as follows:

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year one oil effect monitoring</td>
<td>$69,913.40</td>
</tr>
<tr>
<td>Years two through ten oil effect monitoring</td>
<td>$529,791.30</td>
</tr>
<tr>
<td>Ten years of oil effect monitoring</td>
<td>$599,704.70</td>
</tr>
<tr>
<td>Direct physical restoration measures</td>
<td>$272,126.49</td>
</tr>
<tr>
<td>Total restoration costs</td>
<td>$871,831.19</td>
</tr>
</tbody>
</table>

Average costs per site for oil effect monitoring and direct physical restoration were calculated from the total cost figures by dividing them by the number of sites for which the measures are proposed. The average costs are $59,970.47 per site for oil effect monitoring and $14,322.45 per site for direct physical restoration.

The projections for the numbers of sites injured on which the estimates of gross restoration costs are based were derived from four sets of figures:

1. The projected numbers of injured sites in the draft State University of New York report entitled Exxon Valdez Oil Spill Archaeological Damage Assessment by Albert J. Dekin et al. (1992).
2. The Dekin et al. figures reduced by the percentages corresponding to the number of sites eliminated from consideration by the damage assessment panel because the injuries were not severe enough to require restoration.
3. The number of sites proposed by the panel for oil effect monitoring and
direct physical restoration as percentages of the total number of sites now included in the Alaska Heritage Resource Survey site inventory records for the oil spill area.

4. The number of sites proposed by the panel for oil effect monitoring and direct physical restoration as percentages of the number of sites actually located and examined by Exxon crews during oil spill response activities.

Each of these four figures was multiplied by the average per site costs for oil effect monitoring and direct physical restoration. The resulting gross restoration costs estimates for oil effect monitoring are:

- (1) $31,844,319.57
- (2) $28,126,150.43
- (3) $1,439,291.28
- (4) $3,598,228.20

For direct physical restoration measures, they are:

- (1) $4,840,988.10
- (2) $3,867,061.50
- (3) $658,832.70
- (4) $1,618,436.85

The total gross restoration cost estimates are:

- (1) $36,685,307.67
- (2) $31,993,211.93
- (3) $2,098,123.98
- (4) $5,216,665.05

The gross cost estimates based on the number of sites actually field checked by Exxon (number four above) are seen as reliable indicators of the overall magnitude of archaeological restoration needs resulting from the oil spill.

Two important conclusions are drawn from the results of the work summarized in this paper. First, the ARPA damage assessment model was used successfully to generate credible restoration cost determinations for the documented archaeological injuries of the Exxon Valdez Oil Spill. Second, the ARPA model should be the damage assessment and restoration cost determination standard for archaeological injuries resulting from future oil spills or other similar situations.

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Long-Term Social Psychological Impacts of the *Exxon Valdez* Oil Spill

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During the last decade scientific studies have been conducted on the community impacts of technological disasters (Baum et al., 1982, 1983; Omohundro, 1982; Couch and Kroll-Smith, 1985; Gill and Picou, 1989). Most recently, a number of studies provide empirical evidence which demonstrates that, in contrast to natural disasters, technological disasters produce long-term patterns of stress. These patterns of stress appear to be related to issues of "uncertainty" of extent of contamination (Vyner, 1988), protracted litigation activities (Brown and Mikkelson, 1989; Picou and Rosebrook, 1992), and general sociocultural disruption (Freudenberg and Jones, 1991).

Social impact assessments of the *Exxon Valdez* oil spill have been relatively limited. Studies suggest that subsistence activities of Alaskan natives were initially disrupted by the spill (Fall, 1990; Restoration Planning Work Group, 1990; Dyer et al., 1992). Furthermore, research also reveals the existence of social impacts some 18 months following the spill (Picou et al., 1992). The nature of these impacts included relatively high levels of family, work and personal disruption, as well as continuing patterns of personal stress (Picou et al., 1992).

Given this recent interest in identifying long-term social impacts of technological disasters and the paucity of longitudinal data on this subject, this study will present and evaluate a causal model which depicts long-term social psychological impacts.

A disaster impact assessment design structured the methodological procedures of this research (Gill and Picou, 1991; Picou and Rosebrook, 1992). This approach included standardized indicators of social impacts, random sampling procedures, and a control community comparison. The survey instrument included demographic, social and psychological indicators used in previous disaster research. This research design used stratified random sampling techniques and included personal, telephone and mail surveys over the three year data collection period.

**Impact and Control Community Description**

Cordova was selected as an impacted community because of its economic dependency on commercial fishing and its cultural heritage of subsistence activities. It is located in the southeastern region of Prince William Sound. The community is isolated from other communities by mountains, glaciers, rivers and the sea. No roads have connected Cordova to the outside world since 1964. Incorporated in 1909, the city became an export center for copper mined in the Wrangell mountains to the north. The closing of the copper mines in 1939 led to increasing involvement in commercial fishing. The community population currently fluctuates from 2,500 during the winter to over 4,500 during the summer commercial fishing season.

Cordova fishermen own almost one-half (44%) of all Prince William Sound
herring permits and 55% of all Prince William Sound salmon fishery permits (Stratton, 1989). Subsistence activities (i.e., harvesting, giving, receiving fish, moose, deer, berries, etc.) characterize 90% of Cordova's households (Stratton, 1989) and Alaskan natives make up 18 percent of the population. These and other data classify Cordova as a natural resource community (Dyer et al., 1992). The commercial fishing industry and numerous related businesses link this community directly to seasonal harvests of renewable natural resources.

Petersburg, Alaska was selected as the control community for this study. Petersburg is located on an island in the southeastern part of the state and is relatively isolated with no road connections outside Mitkof Island. Petersburg has a population of 3,500 people, with Alaskan natives comprising approximately 20%. Petersburg's economic base is based on commercial fishing. Petersburg residents also engage in subsistence activities at a rate similar to Cordova (Smythe, 1988; Stratton, 1989).

Data Collection: A stratified random household sample was selected in the Cordova community. In August, 1989, personal interviews with 86 respondents were conducted, reflecting 70 households. Random digit dialing telephone interviews were conducted in Petersburg and Cordova to complete data collection activities for the first year. In 1990, follow-up interviews were conducted by mail and telephone surveys. In 1991, respondents in Cordova were reinterviewed by personal interviews and respondents in Petersburg were once again contacted by telephone.

Indicators and Measures: Information was collected from respondents on demographics, social attitudes, work, family and personal disruption and social psychological stress. Social psychological stress was measured by the "impact of events scale," which identifies two stress components— intrusion and avoidance (Horowitz et al., 1979; Horowitz, 1986).

Statistical Analysis: A series of path models, or structural equation models, were calculated for data available from 1989 to 1991 (Duncan, 1966; Birnbaum, 1981). In general, these models attempt to identify causal relationships between social structural characteristics, social disruption and psychological stress.

Results

Higher levels of intrusive stress and avoidance behavior were observed for the impacted community in 1989, 1990 and 1991. These differences were found to be statistically significant (Pr < .05) when t-tests were applied to compare impact and control community mean scores on the stress indicators. Mean stress scores were found to decline from 1989 to 1991 in the impact community suggesting that, over time, a reduction in the intensity of the social psychological impacts.

The evaluation of the models provided limited support for the hypothesis that social structural characteristics influence social and psychological reactions of victims of technological disasters. The primary predictors of intrusive stress in 1991 included intrusive stress in 1990 and 1989, work disruption in 1989 and continuing social disruption in 1991. Attitudes toward the effectiveness of cleanup operations were found to predict long-term stress. That is, respondents who were most pessimistic about cleanup effectiveness in 1990 tended to be more stressed in 1991. In general, respondents who were male and who
experienced both work and family disruption in 1989 held the most pessimistic views of cleanup effectiveness.

The long-term patterns of social psychological stress found in previous studies of a variety of technological disasters were also observed for residents of the impact community in this research. Higher levels of intrusive stress and avoidance behavior were found to exist in 1989, 1990 and 1991 in the impact community. Over time, levels of stress were found to be declining. For example, mean intrusive stress scores fell from 24.47 in 1989 to 19.32 in 1990 and then further declined to 17.74 in 1991. This general trend suggests a pattern of return to community equilibrium.

Attempts to develop and evaluate causal models of long-term stress resulting from the Exxon Valdez oil spill were modestly successful. Although some intervening variables were found to predict long-term stress, initial stress levels were the most important predictors of later stress levels in the models. Intrusive stress existing some 20 months after the spill was found to be related to perceptions that the cleanup was ineffective. However, the relative effects of both attitudes toward the cleanup and problems experienced from litigation on intrusive stress were small when compared to effects of previous stress levels generated from the spill.

In conclusion, alternatives to linear, additive models may be required to fully understand the complex patterns of long-term stress created by technological disasters in general and the Exxon Valdez oil spill, in particular. Models utilizing interaction terms may provide more accurate explanations. Future analyses of these data will evaluate the utility of this approach.

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The Economic Impacts of the Exxon Valdez Oil Spill on Southcentral Alaska’s Commercial Fishing Industry

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The potential of natural disasters to generate short-term economic benefits for impacted individuals and communities has become an accepted social science notion (Dacy and Kunreuther, 1969; Rogers, 1970; Cochrane, 1975; Wright et al. 1979; Friesema, et al. 1979; Rossi et al. 1983). Unfortunately, the economic dimensions of human-made disasters have not received similar treatment despite the considerable attention that has recently been focused on these events and their sequela (e.g., Erickson, 1976, 1991; Levine, 1982; Couch and Kroll-Smith, 1985; Shrivastava, 1987).

In the case of oil spills, economic research has been largely confined to the estimation of comprehensive damage assessments (Mead and Sorensen, 1970; Burrows et al, 1974a, 1974b; Brown et al. 1983; Grigalunas, 1982; Grigalunas et al. 1986; Assaf et al. 1986). With the exception of work completed by Nelson (1981) and Restrepo (1982) there has been little consideration of the perturbing influences that technological disruptions can have on local and regional economies.

Within the context of recent technological accidents (e.g., Bhopal, Three Mile Island, Love Canal), the *Exxon Valdez* oil spill is distinguished by its widespread physical damage of a highly valued natural environment and its extraordinary economic bonanza (Cohen, 1993). In order to contain the spilled cargo, collect contaminated debris, and clean oiled shorelines a massive emergency response operation was assembled that eventually employed 11,000 local residents and transient laborers at wages exceeding $16 per hour.

However, while these ephemeral windfall profit opportunities were being exploited, the fundamental component of the regional economy was experiencing a downward realignment. In an effort to measure the magnitude of this adjustment, this analysis derives ex post estimates of the oil spill’s economic impacts on southcentral Alaska’s commercial fishing industry during the years 1989 and 1990 in isolation of the considerable financial benefits imparted by the emergency response operation. A three-phase methodology is employed to determine the ex-vessel revenue that would have been earned for each of southcentral Alaska’s eleven major commercial fishery products (chinook, sockeye, coho, pink and chum salmon, king crab, tanner crab, Dungeness crab, Pacific herring sac roe, Pacific halibut, and sablefish) during each of these two years had the oil spill not occurred.

First, estimates of the accident’s harvest volume impacts are constructed using data reported by the Alaska Department of Fish and Game (ADF&G), International Pacific Halibut Commission (IPHC), and the National Marine Fisheries Service (NMFS). The pre-season harvest expectations for each commercial fishery in southcentral Alaska (Prince William Sound, Lower Cook Inlet, and Kodiak Island) were compared to actual yields. In order to ascertain the extent of
contamination from the oil spill, physical monitoring and organoleptic test results were examined for each regulatory jurisdiction that evidenced a harvest deficit in either of the two years under consideration. Harvest volume impacts for each commercial fishery were then apportioned to the accident according to these data. This method led to the conclusion that the oil spill's harvest volume impacts were confined principally to Pacific herring and pink and chum salmon during the 1989 season. No harvest volume reductions attributable to the accident were experienced in 1990.

Second, the Exxon Valdez oil spill was hypothesized to have motivated a fundamental shift in ex-vessel demand for southcentral Alaska's commercial fishery products as retail consumers became fearful of tainted seafood. This effect was estimated with a price-dependent demand model that was variously adapted to the specific characteristics of each of the region's major fish and shellfish species. Independent variables included in these specifications were the seasonal quantity of landed product, national income of major consuming countries, frozen and canned inventory holdings, price of substitutes, and exchange rates between the United States and major consuming countries.

The structural equations derived from this model were estimated by a biased least squares fitting procedure with data for the period 1964-1988. The subsequently derived coefficients were then used to generate ex post forecasts of the ex-vessel prices that would have prevailed for southcentral Alaska's commercial fishery products during 1989 and 1990 in the absence of the oil spill. The predicted ex-vessel prices were then contrasted with their corresponding actual values. On the basis of this technique, the largest ex-vessel price impacts were sustained in both years by Pacific herring sac roe and coho and chum salmon. Noteworthy is the observation that actual ex-vessel prices for Pacific halibut and sablefish exceeded predicted values during both seasons, raising the possibility that some demand substitution of these products least threatened by oil contamination may have occurred.

Finally, the full extent of these estimated harvest volume and ex-vessel price impacts cannot be attributed to the Exxon Valdez oil spill as the commercial fishing industry was concurrently perturbed by several other biological and economic influences in addition to the accident. On the biological side, commercial fishery yields are generally subject to considerable stochastic variability due to numerous environmental factors. For instance, fluctuations in rates of predation, disease mortality, and water temperature can alter interseasonal commercial fishery harvest volumes. Additionally, various forms of human intervention, including regulatory measures and artificial cultivation, can result in harvest volume adjustments.

On the economicside, ex-vessel prices in 1989 and 1990 were influenced by several perturbations that occurred simultaneously to the oil spill. After attaining unprecedented levels in 1988, ex-vessel prices for most Alaskan commercial fishery products began to erode in 1989. This trend was motivated by substantial increases in the volume of salmon produced internationally. Other factors contributing to this decline included excessive wholesale inventories, reduced consumer spending, unfavorable exchange rate adjustments, and suspended