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ARTICLE

PERSISTENCE, TOXICITY, AND LONG-TERM ENVIRONMENTAL IMPACT OF THE *EXXON VALDEZ* OIL SPILL

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Today, twenty years after the oil spill of the *Exxon Valdez*, Alaskans still wonder when the spill will be over. Usually, a major spill can be deemed "over" when all litigation has been settled, oil no longer persists in the environment, and negative effects are no longer detected. The *Exxon Valdez* spill does not meet any of these three criteria.

In addition to the environmental damage, the *Exxon Valdez* oil spill resulted in consequences both legal (e.g., the Oil Spill Pollution Act of 1990) and sociological (e.g., the impact on area residents). Yet the spill has also generated a tremendous amount of scientific knowledge, which will be a lasting legacy for the scientific community. No other oil spill has been studied so intensely (biologically and chemically) for so long.[1] It is unfortunate that the spill occurred in such a productive and pristine habitat as Prince William Sound, yet from a scientific perspective, we are fortunate. Studying the long-term consequences of oil spills in other regions of the world has often been complicated by the background pollution that was already present. For example, it is difficult for researchers to separate the damages from the *Cosco Busan* spill in San Francisco Bay from the damages caused by two centuries of industrialization and urbanization in areas that surround San Francisco Bay. This is not the case with the *Exxon Valdez*. The *Exxon Valdez* disaster has yielded, and will continue to yield, more scientific understanding of the long-term environmental consequences of oil spills than any other spill.

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1. Stanley D. Rice et al., *The* Exxon Valdez *Oil Spill*, *in* LONG-TERM ECOLOGICAL CHANGE IN THE NORTHERN GULF OF ALASKA, 419–520 (Robert B. Spies ed., 2007).

Background

The release of eleven million gallons of Alaska North Slope crude oil from the *Exxon Valdez* in March of 1989 was and continues to be the largest oil spill in U.S. waters.[2] On the third day after the *Exxon Valdez* struck Bligh Reef, 70-knot winds carried the spilled oil south and west, contaminating the western sound and ending any hope of containing the spill.[3] Many of the bays in western Prince William Sound remained heavily contaminated with a thick coating of oil for weeks following the spill. Oil began flowing out of Prince William Sound after about a week, extending down to the Kenai Fjords, Kodiak Island, Cook Inlet, and ultimately reaching the Alaska Peninsula—some five hundred miles from Bligh Reef where the vessel went aground. Massive clean-up efforts began in 1989 and 1990, including mobilizing an army of ten thousand workers spread across the spill area, which ultimately cost Exxon $2.5 billion.[4] This clean-up effort was effective in cleansing the surface oil from the beaches, although less than 10 percent of the spilled oil was recovered from the surface of the water or the surface of beaches. Unknown at the time was the extent and significance of subsurface oil that had penetrated deep into the beaches in western Prince William Sound.

State and federal agencies initiated a series of damage assessment studies immediately after the spill. The Exxon Corporation conducted its own studies as well. The damage assessments were done in anticipation of litigation and were kept secret until after the 1991 settlement.[5] The largest environmental settlement in U.S. history was reached in 1991.[6] The settlement—nearly one billion dollars—was intended to compensate for damages to the natural resources. These funds have been used to reimburse the state and federal governments for their costs in assessing damages and to fund anticipated restoration and protection efforts. Because of this settlement, the *Exxon Valdez* spill is the most studied oil spill in world history, yielding the most comprehensive insight into oil persistence and long-term effects.

Currently, the state and federal governments are arguing over "the reopener clause," thus continuing litigation on natural resource damages. Under this clause, which was part of the 1991 settlement, the state and federal governments could sue for up to an additional $100 million if damages were discovered beyond what was known at the time of the settlement in 1991; in June 2006, the U.S. and Alaska governments notified Exxon of their intent to claim an additional $92 million dollars to compensate for the

2. *Id.*
3. *Id.*
4. *Id.*
5. *Id.*
6. *Id.*

unexpected damages they have been observing.[7] The long-term persistence of oil and the long-term damages ascertained in the last decade fuel this discussion.

Predicted Short-term Effects Versus Unpredicted Long-term Effects

Acute mortalities from short-term exposures are predictable with any spill, but delayed mortalities and impacts have continued, and these were never predicted at the time of the settlement. Many oil spills preceded the *Exxon Valdez* spill, and acute mortalities in many species—particularly in birds and marine mammals—were widely observed.[8] Surface species, such as seabirds, marine mammals, and intertidal invertebrates, are always among the species hit hardest by a spill. *Exxon Valdez* was not an exception. Estimated mortalities based on large numbers of collected carcasses include 3,000–5,000 sea otters and 400,000–700,000 seabirds.[9] Viscerally disturbing photographs were widely exhibited in the national news media.[10] In contrast, impact on the species below the surface, such as fish, is difficult to detect following a spill because carcasses are rarely evident (some sink, but most are consumed quickly by other predators). Contamination on the shoreline is a widely-observed consequence of many spills (*Torrey Canyon*, *Amoco Cadiz*), but there are relatively few studies with long-term measurements of contamination. Even rarer are the long-term contamination studies that link oil spills to long-term biological effects.

Long-term population effects are very difficult to detect and often require good population data prior to a spill event, though such data is rarely available. While the acute mortalities based on oiled carcasses are easily attributed to an oil spill, long-term consequences are not. Delayed mortalities are not often detected and are sometimes confounded by other factors and other sources of contamination, particularly in spills that occur near urban areas. Hence, long-term negative effects of previous spills are not usually identified. However, when they began to be recognized in the late 1990s in Prince William Sound, where urbanization and prior spills are not confounding, they surprised many in the scientific community. Following are case history discussions of long-term effects and the interaction of some species with oil persistence: killer whales, pink salmon, sea otters, and herring. Other species were surely affected, but the evidence of long-term oil

7. *Exxon Valdez* Oil Spill Trustee Council, Legacy of an Oil Spill 20 Years after *Exxon Valdez* 6 (2009).

8. National Academy of Science, Oil in the Sea: Inputs, Fates, and Effects (Nat'l Acad. Press ed., 1985).

9. Robert B. Spies et al., *The Effects of the* Exxon Valdez *Oil Spill on the Alaskan Coastal Environment*, *in* Proceedings of the *Exxon Valdez* Oil Spill Symposium 1–16 (Stanley D. Rice et al. eds., 1996).

10. *Exxon Valdez* Oil Spill Trustee Council, *supra* note 7.

persistence and long-term effects in these species is the most comprehensive, except for herring, which remain an enigma to this day.

Case Study: Killer Whales, Unexpected Long-term Population Effects

Even though there were massive acute mortalities in many species, particularly birds, it was expected that the affected populations would recover in a few generations.[11] The acute mortalities in killer whales were not detected in the first few years (killer whale carcasses sink, so none were recovered at the time of the spill), but after ten years, the long-term consequences began to be realized.

Killer whales are individually identifiable, and fortunately, in Prince William Sound they were photographed for identification starting in 1984, five years prior to the spill.[12] Thus, researchers knew the numbers and associations of the whales at the time of the spill. Two groups of killer whales were photographed in slicks of oil in the weeks following the spill and both groups lost 40 percent of their population in the year after the spill.[13] One of these—the AB pod—is a "resident" fish-eating group of killer whales. Although the AB pod does show some signs of population recovery, it will take decades to recoup the numbers that were lost in the year after the spill. The second group is a small, unique population known as "AT1." They are "transient" killer whales that feed on marine mammals. They show no signs of recovery and continue to decline. Because no reproductive females are left, this pod will become extinct.

Whale pods are integral, matrilineal families.[14] Therefore, a spill that kills any of the key members of the pod, especially reproductive-age or nursing females, can have far-reaching consequences. The reproductive capacity of both pods was reduced by the loss of females, which even under ideal conditions have a low reproductive rate, with only about half of newborn calves surviving. Since pods are matrilineal, the loss of these females means that the leaders of the pod are also lost. Some of the females that disappeared after the spill also had young offspring that died in the first few years after the spill, likely due to the loss of their mothers.

The losses to killer whale populations resulted primarily from the initial acute exposure to the spill.[15] As mammals, whales must surface in order to breathe. During the spill, the air above the oil slick was heavily contami-

11. Charles H. Peterson et al., *Long-term Ecosystem Response to the Exxon Valdez Oil Spill*, 302 Sci. Mag. 2082, 2082–86 (2003).

12. Craig O. Matkin et al., *Ongoing Population-level Impacts on Killer Whales* Orcinus Orca *Following the 'Exxon Valdez' Oil Spill in Prince William Sound, Alaska*, 356 Marine Ecology Progress Series 259, 259–81 (2008).

13. *Id.*

14. *Id.*

15. *Id.*

nated with toxic fumes, so when the whales surfaced to breathe, they inhaled contaminated air. Such was the case for all mammal species.

Killer whale losses from the acute initial exposures are examples of the length of time for recovery of long-lived species with low reproductive rates. Other species with short generation times have the capacity to recovery much quicker, if conditions are right (no further oil exposure, productive conditions to support juvenile recruitment). For species that significantly affect the structure of an ecosystem (apex predators, or forage species important in energy transfer), long-term recoveries will have a long-term impact on the recovery state of the ecosystem.

LONG-TERM RECOVERY: NEW DAMAGE FROM CONTINUING EXPOSURE

As long as oil persists, new damage to organisms can occur. After a spill, most attention is focused on the recovery of populations affected by the initial impact of a spill. Scientists have long suspected that "chronic exposure" to residual oil may cause further harm,[16] but the presence of other anthropogenic disturbances (over fishing, loss of habitat from development, non-point source pollution in estuaries) make it very difficult to distinguish harm from a specific spill event, other environmental issues, or even natural population swings. The *Exxon Valdez* spill, however, occurred in a pristine ecosystem, making it an ideal case study for identifying the effects (if any) of oil persistence. The next section discusses what scientists learned about oil persistence from the *Exxon Valdez* spill; it is followed by two case studies that detail the specific impact that lingering oil had on pink salmon and sea otters.

Oil Persistence—Longer than Expected

Oil lingers underneath more than half of the beaches of Prince William Sound, although visitors today would find the surface of the beaches clean.[17] Exxon's initial cleaning efforts, followed by violent winter storms, were very effective in removing oil that was on the surface of the beach.[18]

When Exxon and the State of Alaska reached a settlement in 1991, no one expected that oil from the spill would persist for another twenty years, or even ten years.[19] But when the national news media visited a few selected beaches for an update on the ten-year anniversary of the spill, they discovered dark liquid oil just underneath the beaches' clean-appearing surfaces. Additionally, a few species were not recovering at the expected rate in some areas, but continuing exposure to oil was not suspected as the pri-

16. Peterson et al., *supra* note 11.

17. Jeffrey W. Short et al., *Estimate of Oil Persisting on the Beaches of Prince William Sound 12 Years After the Exxon Valdez Oil Spill,* 38 ENVTL. SCI. & TECH. 19, 19–25 (2004).

18. *Id.*

19. *EXXON VALDEZ* OIL SPILL TRUSTEE COUNCIL, *supra* note 7.

mary cause—at least not until the national news media cameras captured new images of liquid oil in the beaches.[20]

This media coverage sparked a demand for further study. In 2001, intensive field surveys found oil in over half of the sites examined in Prince William Sound that had been heavily or moderately contaminated in 1989–91.[21] This was a very extensive study; ninety-one beach sites were examined over a four-month period (researchers dug over nine thousand pits). Oil was found at different levels of intensity from light sheen to heavy oil, where the pit would literally fill with oil.[22] Researchers estimated that approximately 16,000 gallons (60,000 liters) of oil remained.[23] The survey also revealed an increasing number of oiled pits from the upper intertidal down to the mid intertidal zone—the amount of oil found exceeded the projected estimates. In 2003, additional surveys determined that, while the majority of subsurface oil was in the mid-intertidal zone, a significant amount was also in the lower intertidal.[24] The oil in the lower intertidal was an important finding because this tidal zone is biologically rich with mussels, clams, algae and other fauna. The revised estimate of oil was now approximately 21,000 gallons (80,000 liters).[25] Additional surveys outside Prince William Sound have documented lingering oil on the Kenai Peninsula and the Katmai Coast as well—over 450 miles away.[26]

Oil Source and Toxicity

The subsurface oil was identified as coming from the *Exxon Valdez* spill. Weathering (physical or chemical degradation of the complex mixture within the oil) of the subsurface oil is very low because little or no oxygen is available to the oil patches below the surface. The lack of weathering in subsurface oil makes it easier to chemically identify the source of the spilled oil, because the hydrocarbon composition of the subsurface oil remains very similar to the original oil spilled. The lightest fraction of aromatic hydrocarbons (single-ring compounds like benzene and toluene) are missing, but most of the toxic two- to four-ring polycyclic aromatic hydrocarbons (PAH) remain intact and toxic, and in the same proportions as *Ex-*

20. *Id.*

21. Short et al., *supra* note 17.

22. *Id.*

23. *Id.*

24. Jeffrey W. Short et al., *Vertical Distribution and Probability of Encountering Intertidal Exxon Valdez Oil on Shorelines of Three Embayments within Prince William Sound, Alaska*, 40 Envtl. Sci. & Tech. 3723, 3723–29 (2006).

25. *Id.*

26. Jeffrey W. Short et al., *Slightly Weathered* Exxon Valdez *Oil Persists in Gulf of Alaska Beach Sediments after 16 Years*, 41 Envtl. Sci. & Tech. 1245, 1245–50 (2007).

xon Valdez oil collected in the first weeks of the spill. Because there is virtually no weathering, the oil remains liquid, mobile, and toxic.[27]

Loss of Oil

The clean-up efforts in the first years after the spill were quite intense. An army of ten thousand workers cleaned the surface of the beaches during the summers of 1989 and 1990, and Mother Nature scrubbed the beaches in the winter with violent storm activity and two tides each day.[28] It was assumed that these processes would be more than sufficient to remove all of the oil, but they were not.

Natural processes are currently removing the oil at a rate of zero to four percent per year, with low-energy beaches having loss rates that are near zero.[29] Beaches with residual oil three to six inches below the surface will likely have oil remaining for decades, sparking debates as to whether more clean-up is necessary or whether it would do more harm than good.[30] The long-term persistence of the oil is an issue relevant to the "reopener clause" because these possible funds might be used for further clean-up, but only if the source is the *Exxon Valdez* spill. Because the source of this oil is critical and contested, there have been several suggestions that the source of the subsurface oil remaining in the beaches is from either natural oil seeps or a spill from storage tanks in the town of Valdez during the 1964 earthquake. The chemical fingerprinting has been convincing that the remaining *Exxon Valdez* oil continues to far exceed any other local sources.[31]

Bioavailability

The oil remaining today is only significant if it is biologically available to organisms and exposures to oil continue; such is the case today. The evidence of long-term bioavailability is overwhelming. Direct chemical measurements have confirmed that mussels and clams from many widely dispersed beaches continue to sequester oil hydrocarbons in their tissues.[32] A series of studies in 2004, using passive samplers, also demonstrated that subsurface oil patches still leaked PAH and stimulated a P450 biomarker response in fish. Direct measurement of hydrocarbons in tissues of

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27. *Id.*; *see also* Rice et al., *supra* note 1; Michael L. Murphy et al., *Recovery of Pink Salmon Spawning Areas after the* Exxon Valdez *Oil Spill*, 128 TRANSACTIONS OF THE AM. FISHERIES SOC'Y. 909, 909–18 (1999).

28. Rice et al., *supra* note 1.

29. Short et al., *supra* note 26.

30. *Id.*

31. Jeffrey W. Short et al., *Natural Hydrocarbon Background in Benthic Sediments of Prince William Sound, Alaska: Oil vs. Coal*, 33 ENVTL. SCI. & TECH. 34, 34–42 (1999).

32. Allen K. Fukuyama et al., *Effects of Residual* Exxon Valdez *Oil on Intertidal* Protothaca staminea*: Mortality, Growth, and Bioaccumulation of Hydrocarbons in Transplanted Clams*, 40 MARINE POLLUTION BULL. 1042, 1042–50 (2000); Mark G. Carls et al., *Persistence of Oiling in Mussel Beds after the* Exxon Valdez *Oil Spill,* 51 MARINE ENVTL. RES. 167, 167–90 (2001).

vertebrates (fish, birds, mammals) is seldom an effective measure of exposure because vertebrates have the physiological capacity to metabolize and excrete hydrocarbons, and can do this relatively quickly. For vertebrates, the presence of elevated P450 enzymes (special enzymes that can metabolize and degrade oil) is a more effective method to evaluate exposures to oil. Elevated P450 biomarker enzymes have been found in fish, harlequin ducks, and sea otters for long periods of time.[33]

Case Study: Pink Salmon—the First "Big Wow"

Three studies showed impact on pink salmon in 1989, which was not surprising given the intensity and wide distribution of the spilled oil.[34] Pink salmon fry that first out-migrated to salt water in the days and weeks following the spill had poor growth,[35] and like many species, poor growth in the early juvenile stages leads to increased predation and fewer adult returns. In addition, the monitoring of embryo mortalities in intertidal spawning streams—a routine measure by the State of Alaska Department of Fish and Game to predict future returns—found elevated embryo mortalities in the oiled streams.[36] Together, these first-year impacts indicated that approximately two million adults that should have returned to Prince William Sound did not.[37]

More surprising was the continued elevated embryo mortalities in the intertidal streams in oiled habitats for four more years, from 1989 to 1992.[38] Elevated embryo mortalities in each of these years indicated that there was "new damage" (i.e., not a continuation of the first-year effect), though the

33. Michael Wiedmer et al., *Cytochrome P-450 Induction and Histopathology in Preemergent Pink Salmon from Oiled Spawning Sites in Prince William Sound*, *in* Proceedings of the *Exxon Valdez* Oil Spill Symposium, *supra* note 9, at 509, 509–17; J.L. Bodkin et al., *Sea Otter Population Status and the Process of Recovery from the 1989 'Exxon Valdez' Oil Spill*, 241 Marine Ecology Progress Series 237, 237–53 (2002); Daniel Esler et al., *Harlequin Duck Population Recovery Following the 'Exxon Valdez' Oil Spill: Progress, Process and Constraints*, 241 Marine Ecology Progress Series 271, 271–86 (2002).

34. Rice et al., *supra* note 1.

35. Mark Willette, *Impacts of the* Exxon Valdez *Oil Spill on the Migration, Growth, and Survival of Juvenile Pink Salmon in Prince William Sound*, *in* Proceedings of the *Exxon Valdez* Oil Spill Symposium, *supra* note 9, at 533, 533–50; A.C. Wertheimer & A.G. Celewycz, *Abundance and Growth of Juvenile Pink Salmon in Oiled and Non-oiled Locations of Western Prince William Sound after the* Exxon Valdez *Oil Spill*, *in* Proceedings of the *Exxon Valdez* Oil Spill Symposium, *supra* note 9, at 518, 518–32.

36. Brian G. Bue et al., *Effects of the* Exxon Valdez *Oil Spill on Pink Salmon Embryos and Preemergent Fry*, *in* Proceedings of the *Exxon Valdez* Oil Spill Symposium, *supra* note 9, at 619, 619–27 [hereinafter Bue et al., *Pink Salmon Embryos*]; Brian G. Bue et al., *Evidence of Damage to Pink Salmon Populations Inhabiting Prince William Sound, Alaska, Two Generations after the* Exxon Valdez *Oil Spill*, 127 Transactions of the Am. Fisheries Soc'y. 35, 35–43 (1998) [hereinafter Bue et al., *Evidence of Damage*].

37. Harold J. Geiger et al., *A Life History Approach to Estimating Damage to Prince William Sound Pink Salmon Caused by the* Exxon Valdez *Oil Spill*, *in* Proceedings of the *Exxon Valdez* Oil Spill Symposium, *supra* note 9, at 487, 487–98.

38. Bue et al., *Evidence of Damage*, *supra* note 36, at 35–36.

mechanism of exposure was not readily apparent. Visible oil was never observed in the spawning redds, but only along the sides of the stream. These observations of elevated embryo mortalities stimulated field studies to verify an exposure mechanism and lab studies to verify that extremely low doses of exposure could cause such effects.

The exposure mechanism was not confirmed in the field for several years. Initially during the spill, scientists observed the presence of oil in the banks, but after clean-up efforts and winter storm activity had removed the visible oil from the surface, people assumed the oil was gone. But six years after the spill, oil was discovered in the stream banks, suggesting that oil was present when elevated embryo mortalities were detected a couple of years earlier.[39] The mechanism by which oil traveled from the porous gravel sides of the stream to the intra-gravel salmon redds was demonstrated in a dye study; yet it was obvious from this study that only extremely low concentrations could get to the salmon redds—not high acute type dose levels.[40]

Extremely Low Concentrations of PAH Affect Embryos

A series of elegant laboratory exposure tests confirmed that long-term low-level exposure of embryos to oil will result in mortalities and sub-lethal effects that decrease adult returns.[41] In these experiments, pink salmon embryos were exposed in a laboratory to simulate the wild environment, where pink salmon embryos remain in the spawning redds for about seven to nine months before they emerge as fry and go to sea. In these tests, exposed and control fry at emergence from the spawning gravels were tagged and released to the wild, where they mature in 1.3 years and return to their natal streams (in this case, back to the hatchery where their exposures were as embryos). These tests allowed for the assessment of fitness of exposed but normal "looking" emergent fry by testing their survival in the wild. This unusual laboratory/field experiment works because salmon return to the natal stream, where the researchers could separate exposed and control adults by deciphering the tags. A series of tests over a number of years confirmed that low-level exposures would directly affect short-term survival, and sub-lethal doses (down to about five parts per billion PAH) would affect adult returns.[42] This was a significant measurement; it showed that the impacts of

39. Murphy et al., *supra* note 27.

40. Mark G. Carls et al., *Pink Salmon Spawning Habitat is Recovering a Decade after the* Exxon Valdez *Oil Spill*, 133 TRANSACTIONS OF THE AM. FISHERIES SOC'Y. 834, 834–44 (2004).

41. *See* Rice et al., *supra* note 1.

42. Ron A. Heintz et al., *Sensitivity of Fish Embryos to Weathered Crude Oil: Part II. Increased Mortality of Pink Salmon (*Oncorhynchus gorbuscha*) Embryos Incubating Downstream from Weathered* Exxon Valdez *Crude Oil*, 18 ENVTL. TOXICOLOGY & CHEMISTRY 494, 494–503 (1999); Ron A. Heintz et al., *Delayed Effects on Growth and Marine Survival of Pink Salmon* Oncorhynchus Gorbuscha *after Exposure to Crude Oil during Embryonic Development*, 208 MARINE ECOLOGY PROGRESS SERIES 205, 205–16 (2000).

exposure were dose-related and were verified in experiments in other brood years.[43] The results indicated that embryos are particularly sensitive to low parts per billion PAH—about three orders of magnitude more sensitive, in fact, than short-term toxicity tests from the 1970s had predicted.[44]

Case Study: Lack of Recovery in Sea Otters

Local populations of sea otters in heavily oiled areas have not recovered, although the overall population numbers in western Prince William Sound have recovered. This lack of recovery in the heavily oiled areas was first noticed in the mid-1990s and was presumed to be food related.[45] Sea otters lack the thick insulating blubber found in other marine mammals and rely on a very high caloric intake to fuel a very high metabolic rate. Sea otters consume about 25 percent of their body weight each day and dig many pits while foraging for their preferred food item, clams. Food availability was higher in oiled areas than non-oiled areas (because there were fewer predators in the oiled areas), so it was eliminated as a reason for the lack of recovery. Attention then focused on oil since otters do dig some of their pits in the lower intertidal zone where oil and clams overlap. The area where the sea otter population had recovered the least was the lower pass area of Northern Knight Island; this stretch of beaches was also the area where the pit digging study found the highest concentration of heavily oiled sediments. In adjacent Herring Bay, arguably the hardest-hit bay in the region, no otters could be found.[46] The elevated P450 in sea otters from the Northern Knight Island area is a further indication of their chronic exposure to oiled sediments. Evidence is convincing that otters in this area have not recovered to pre-spill numbers because of chronic exposure to toxic oil.

Other species that forage in the lower intertidal zone also struggle. Overwintering harlequin ducks in the same northern Knight Island area have elevated P450 (indicating chronic oil exposure) and higher mortality rates in the winter.[47] Other intertidal species are likely affected (like clams, polycheate worms and mussels, but the evidence to support effects is not strong).

Together, all of these species enhance the argument for conducting more cleaning in the intertidal environment to remove the lingering oil and source of continuing exposure. Some would argue this should have been done immediately after the spill, and that to do so now might cause more harm. The foraging activity occurring now, particularly the pit digging by otters in the lower intertidal, is probably the leading "restoration" effort that still continues by disturbing the intertidal sediments in the lower zone. This

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43. Rice et al., *supra* note 1.
44. *Id.*
45. Bodkin et al., *supra* note 33.
46. Rice et al., *supra* note 1.
47. Esler et al., *supra* note 33.

disturbance releases small amounts of oil at a time and exposes the oil to oxygen and physical dissolution. Although it will take time, these processes will remove the oil slowly, but at a cost to the species causing the disturbance. However, this appears to be at a rate that the ecosystem can tolerate.

Case Study: The Enigma of Pacific Herring in Prince William Sound

Pacific herring were affected in 1989 by the spill,[48] and the herring numbers in Prince William Sound are still too low to sustain a commercial fishery. Compared to other years, the production of juveniles from the 1989 spawn was very low, the lowest on record. However, that alone does not explain the present low populations of Prince William Sound herring because the population is made up of about seven to ten different brood years. Their population crash was detected in 1993, four years after the spill.[49] Herring populations historically fluctuate and can be affected by a number of factors, including predation, diseases, food availability, and other oceanographic factors.[50] These factors greatly complicate the evaluation of the oil spill as a major contributor to the population crash, and scientists still debate whether the decline was directly linked to the spill.

More importantly, why have the herring not recovered? Herring fisheries were an important part of Alaska's economy prior to the spill, but herring are even more important to the local ecosystem because of their role in the transfer of energy from zooplankton to many important predators, ranging from salmon to birds and marine mammals.[51] Prince William Sound cannot be considered recovered until healthy herring populations have returned.

The mystery of why the herring have not yet recovered has become the focus of *Exxon Valdez* Trustee Council studies.[52] Herring populations are driven by complicated forces, including disease, predation, and oceanographic dynamics. Any proposed restoration for this species will require a careful understanding of these complex dynamics.

Dueling Scientists: How Can You Believe These Results?

As the case for long-term oil persistence and impacts affecting several species has developed over the last twenty years, Exxon-sponsored scientists have consistently questioned and criticized the government studies in-

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48. Rice et al., *supra* note 1.
49. *Id.*
50. *Id.*
51. Herring are rich in natural oils and are key to the recovery of some seabird populations.
52. The *Exxon Valdez* Trustee Council (three state and three federal natural resource Trustees) was created after the 1991 settlement to administer the funds for the purposes of restoration and habitat protection.

volved, in public forums as well as in journals.[53] These opposing views create a sense of uncertainty that requires an extraordinarily high degree of scientific expertise to resolve independently, leaving most members of the public to rely on indirect means of assessing veracity. Litigation continues (regarding the "reopener clause"), so the motivation to challenge government-sponsored studies also continues.

The focus of these challenges usually involved two fundamental issues: statistical power and source of the lingering oil. Statistical power in the government-sponsored studies typically exceeds that of studies sponsored by Exxon.[54] In the case of pink salmon field studies, Alaska Department of Fish and Game examined more oiled streams (ten, compared to five by Exxon), for more years (nine, compared to one), and sampled far more embryos per stream (2,500, compared to 500).[55] Studies of *Exxon Valdez* oil persistence by government scientists were long criticized by Exxon scientists—first on the amount of oil found in the environment, and second on the origins of the found oil.[56] Alternative suggestion on sources other than *Exxon Valdez* spill were seeps in the Gulf of Alaska and oil spilled from storage tanks at former cannery sites. In contrast, more rigorous studies by government scientists using more sensitive methods demonstrated that most of the claims made in the Exxon-supported studies were untenable.[57]

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53. Rice et al., *supra* note 1.

54. Charles H. Peterson et al., *Sampling Design Begets Conclusions: The Statistical Basis for Detection of Injury to and Recovery of Shoreline Communities after the 'Exxon Valdez' Oil Spill*, 210 MARINE ECOLOGY PROGRESS SERIES 255, 255–83 (2001).

55. *See* Bue et al., *Evidence of Damage*, *supra* note 36, at 35; E.L. Brannon et al., *An Assessment of Oil Spill Effects on Pink Salmon Populations Following the Exxon Valdez Oil Spill – Part 1: Early Life History*, *in* EXXON VALDEZ OIL SPILL: FATES AND EFFECTS IN ALASKAN WATERS 548, 548–84 (Peter G. Wells, et al. eds., 1995); E.L. Brannon et al., *Results from a Sixteen Year Study on the Effects of Oiling from the Exxon Valdez on Adult Pink Salmon Returns*, 52 MARINE POLLUTION BULL. 892, 892–99 (2006).

56. *See* Short et al., *supra* note 17; Short et al., *supra* note 24; Short et al., *supra* note 31; *see also* Paul Boehm et al., *Resolving the Origin of the Petrogenic Hydrocarbon Background in Prince William Sound, Alaska*, 35 ENVTL. SCI. & TECH. 471, 471–79 (2001); Paul Boehm et al., *Assessment of Polycyclic Aromatic Hydrocarbon Exposure in the Waters of Prince William Sound after the Exxon Valdez Oil Spill: 1989–2005*, 54 MARINE POLLUTION BULL. 339, 339–67 (2007); Paul D. Boehm et al., *Potential for Sea Otter Exposure to Remnants of Buried Oil from the Exxon Valdez Oil Spill,* 41 ENVTL. SCI. & TECH. 6860, 6860–67 (2007); David S. Page et al., *Pyrogenic Polycyclic Aromatic Hydrocarbons in Sediments Record Past Human Activity: A Case Study in Prince William Sound, Alaska*, 38 MARINE POLLUTION BULL. 247, 247–60 (1999); David S. Page et al., *A Holistic Approach to Hydrocarbon Source Allocation in the Subtidal Sediments of Prince William Sound, Alaska, Embayments*, 3 ENVTL. FORENSICS 331, 331–40 (2002); Robert J. Huggett et al., *Biomarkers of PAH Exposure in an Intertidal Fish Species from Prince William Sound, Alaska: 2004–2005*, 40 ENVTL. SCI. & TECH. 6513, 6513–17 (2006); David S. Page et al., *Polycyclic Aromatic Hydrocarbon Sources Related to Biomarker Levels in Fish from Prince William Sound and the Gulf of Alaska*, 38 ENVTL. SCI. & TECH. 4928, 4928–36 (2004).

57. *See* Jeffery W. Short et al., *An Evaluation of Petrogenic Hydrocarbons in Northern Gulf of Alaska Continental Shelf Sediments – The Role of Coastal Oil Seep Inputs*, 38 ORGANIC GEOCHEMISTRY 643, 643–70 (2007); Katherine R. Springman et al., *Semipermeable Membrane Devices Link Site-specific Contaminants to Effects: Part 1 – Induction of CYP1A in Rainbow Trout*

Long-term controversial issues, driven by the litigation process, such as tobacco safety or anthropogenic-driven climate change, create a confusing background of dueling scientists, making it difficult for the public to sift through large quantities of technical information. Peer reviewed publications that stand the test of time eventually have the best chance to resolve these complex long-term controversies.

Implications for the Future

The *Exxon Valdez* spill will continue to affect legal, sociological, and scientific systems. The highly-visible habitat contamination and the highly-publicized images of bird carcasses immediately after the spill fueled the passing of the Oil Spill Pollution Act of 1990, which mandated that oil tankers be built with double hulls, established regional watch dog groups, and created a host of specific regulations dealing with oils spills. The persistence of oil and its long-term impact, although less visually disturbing, will also have lasting influence on the science of oil spills, and probably on future legislation. The studies finding long-term persistence and long-term effects will likely influence the decision-making processes in future spills, including the methods of cleaning and restoration and the degree of cleaning needed to prevent further damage. The use of dispersants following a spill will receive more consideration. The effects on embryos in the parts per billion of PAH will also spur change, including change in the legislation/regulations that allow permissible levels of PAH in receiving waters. Most importantly, the well-studied consequences of the *Exxon Valdez* spill put a time element into the equation by recognizing how long it takes for an ecosystem to heal itself. No other spill has been able to give us this understanding, and no other spill will have such a far-reaching impact into the future.

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from Contaminants in Prince William Sound, Alaska, 66 MARINE ENVTL. RES. 477, 477–86 (2008); Jeffrey W. Short et al., *Semipermeable Membrane Devices Link Site-specific Contaminants to Effects: Part II – A Comparison of Lingering Exxon Valdez Oil with Other Potential Sources of CYP1A Inducers in Prince William Sound, Alaska*, 66 MARINE ENVTL. RES. 487, 487–98 (2008); *see also* Gerald K. Van Kooten, et al., *Low-maturity Kulthieth Formation Coal: A Possible Source of Polycyclic Aromatic Hydrocarbons in Benthic Sediment of the Northern Gulf of Alaska*, 3 ENVTL. FORENSICS 227, 227–41 (2002).