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Editorial

Spatial and temporal ecological variability in the northern Gulf of Alaska: What have we learned since the *Exxon Valdez* oil spill?

1. Introduction

This special issue examines oceanographic and biological variability in the northern Gulf of Alaska region with an emphasis on recent monitoring efforts of the Gulf Watch Alaska (GWA) and Herring Research and Monitoring (HRM) programs funded by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC). These programs are designed to improve our understanding of how changing environmental conditions affect Gulf of Alaska ecosystems and the long-term status of resources injured by the *Exxon Valdez* oil spill.

The northern Gulf of Alaska shelf and large estuaries of Prince William Sound and Cook Inlet form a productive, dynamic marine region that supports numerous fish, shellfish, bird, and mammal populations. Pelagic and nearshore ecosystems in this region are subject to large-scale variability from both natural and anthropogenic sources. Oceanographic and meteorological conditions across the region vary on seasonal, interannual, and decadal time scales in response to different modes of climate variation in the North Pacific, including El Niño/La Niña events (Weingartner et al., 2002), the Pacific Decadal Oscillation (Mantua et al., 1997), and the North Pacific Gyre Oscillation (Di Lorenzo et al., 2008). Recently, the 2014–2016 Pacific marine heat wave caused unprecedented warming in the northern Gulf of Alaska and ecological changes associated with this event are being assessed (Bond et al., 2015; Di Lorenzo and Mantua, 2016; Walsh et al., in press). Some climate variations have driven biological "regime shifts" during which species assemblages have changed quickly and drastically across the Gulf of Alaska region. A well-documented regime shift occurred in 1976/1977 when there was a transition from shellfish to fish-dominated fisheries in Alaskan waters associated with a shift from a negative to positive phase of the Pacific Decadal Oscillation and warming in the Gulf of Alaska (Anderson and Piatt, 1999). Additional climate-driven biological changes in the North Pacific have been inferred from climatological and biological datasets (Batten and Welch, 2004; Hare and Mantua, 2000). Future changes in ocean temperature, ocean acidification, freshwater inputs, and sea level rise associated with climate variations and long-term change will continue to affect pelagic and nearshore ecosystems in the northern Gulf of Alaska shelf.

Anthropogenic effects in the northern Gulf of Alaska include marine harvest practices such as large biomass removals, hatchery-enhanced salmon fisheries, point and non-point sources of pollution, and the *Exxon Valdez* oil spill. The oil tanker *Exxon Valdez* ran aground in Prince William Sound, Alaska, shortly after midnight on March 24, 1989, spilling approximately 11 million gallons of crude oil: the largest marine oil spill in the United States at the time. In the first week the oil spread throughout the central and western portions of Prince William Sound and reached the Alaska Coastal Current in the Gulf of Alaska. Once in the Alaska Coastal Current the oil was transported into lower Cook Inlet and along Shelikof Strait, up to 750 km from the location of the spill (Fig. 1). The spill's impact on the ecosystem was tremendous, with estimated losses of 250,000 seabirds, 2800 sea otters, 300 seals, and unknown numbers of fish and marine organisms (Wolfe et al., 1994). A $900 million civil settlement was awarded for damages resulting from the oil spill in 1991, with the funds to be used for restoration activities, including research and monitoring.

The EVOSTC, which includes three state and three federal agency trustees, was established to oversee the settlement funds. In 1994, the EVOSTC adopted a restoration plan that established guidelines for research, monitoring, and general restoration activities (EVOSTC, 1994). Since that time, the EVOSTC has provided funding for research and monitoring activities throughout the spill-affected area. Over the years the funding has supported hundreds of individual research and monitoring projects and several integrated research programs. Two overarching themes materialized during the initial post spill period. One was a paradigm shift in post-spill oil ecotoxicology, as Peterson et al. (2003) noted, "moving from acute toxicity based on single species toward an ecosystem-based synthesis of short-term direct plus longer-term chronic, delayed, and indirect impacts." The second was that "the distinction between the effects of the oil spill and other natural or anthropogenic stressors was not clearly delineated" and that these natural and human perturbations could mask or hinder recovery of some resources injured by the spill (EVOSTC, 2010). With this knowledge, and recognizing that funding for future restoration was limited, the EVOSTC identified five areas of focus for the remaining restoration funds to be spent over an expected 20-year period: (1) herring, (2) lingering oil, (3) long-term monitoring of marine conditions and injured resources, (4) harbor protection and marine restoration, and (5) habitat acquisition and protection (EVOSTC, 2010).

Two long-term integrated programs arose from the EVOSTC decision: long-term monitoring of environmental conditions and injured resources under the GWA program (which included evaluation of lingering oil during the first five years of the program) and research and monitoring focused on Pacific herring (*Clupea pallasii*) in Prince William Sound, a species considered not recovering, under the HRM program. The multi-disciplinary, integrated ecosystem studies funded by the EVOSTC provide an ability to examine spatial and temporal environmental variability in the physical and biological environment, for both nearshore and pelagic ecosystems. The efforts of the GWA and HRM programs also extend and build on long-term

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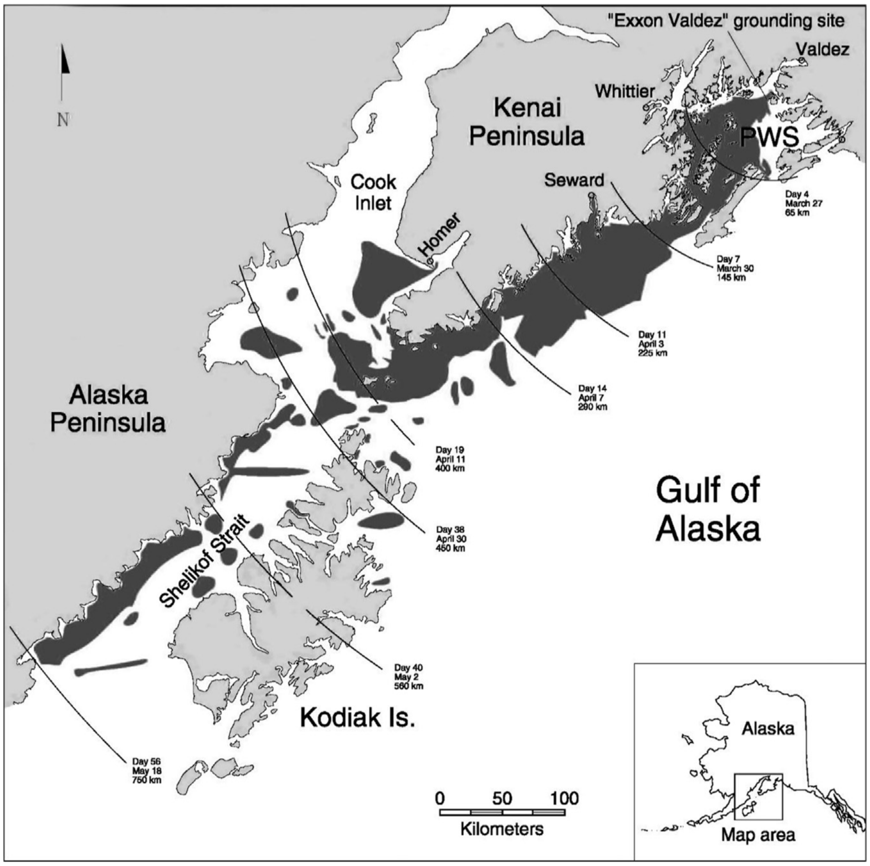

Fig. 1. Map showing the spill affected region and timeline as *Exxon Valdez* oil progressed southwest out of Prince William Sound and into the northern Gulf of Alaska (Data from Gundlach et al., 1990; Reprinted from Spies, 2007).

monitoring and research from previous studies in the Gulf of Alaska. Prior ecosystem studies include the Gulf of Alaska Outer Continental Shelf Environmental Assessment Program conducted from the 1970s to 1990s by the Minerals Management Service (predecessor agency of the Bureau of Ocean Energy Management) and the National Oceanic and Atmospheric Administration (NOAA); the EVOSTC-funded Sound Ecosystem Assessment, Alaska Predator Ecosystem Experiment, and Nearshore Vertebrate Predator programs conducted in the 1990s; the Northeast Pacific Global Ocean Ecosystem Dynamics study funded by the National Science Foundation, NOAA, and National Aeronautics and Space Administration in the 2000s; and the North Pacific Research Board's Gulf of Alaska Integrated Ecosystem Research Program in the 2010s.

1.1. Long-term ecosystem monitoring: Gulf Watch Alaska

The GWA ecosystem monitoring program builds on previous monitoring efforts and research programs in the Gulf of Alaska, which demonstrated the importance of long-term observations and integration of information across scientific disciplines to understand species and ecosystem responses to environmental and anthropogenic variability in the region (Mundy, 2005; Peterson et al., 2003). The overall goals of the GWA program are to monitor species populations and resources injured by the *Exxon Valdez* oil spill in conjunction with factors other than oil that may inhibit recovery or adversely affect recovered species, such as changing climate and oceanographic and ecological conditions. Objectives of the program include sustaining and building on long-term ecosystem monitoring data sets, providing those data to a wide variety of users, and improving use of ecosystem data for management of *Exxon Valdez* oil spill-injured species, through development of information and science synthesis products.

Monitoring efforts in the GWA program include projects that evaluate environmental drivers (oceanographic conditions and primary and secondary productivity), pelagic food webs (forage fish, marine birds, and whales), nearshore food webs (including macroalgae, benthic invertebrates, and vertebrate predators) and lingering oil in Prince William Sound, Resurrection Bay, the Gulf of Alaska shelf, lower Cook Inlet, and Shelikof Strait. The integrated program began in 2012, and includes long-term time series that began before or in response to the 1989 *Exxon Valdez* oil spill, as well as efforts that were initiated later to better understand the lack of recovery of some injured species, ecosystem responses to changing marine conditions, and ecological relationships in the region. The EVOSTC has planned for a 20-year monitoring program, conducted in five-year phases, and GWA is currently in the second phase (2017–2021) of that effort. The GWA program is closely coordinated with the HRM program and provides monitoring data on oceanographic conditions, forage fish, and herring predator populations to the HRM program.

1.2. Herring Research and Monitoring

Pacific herring, hereafter referred to as ‘herring’, are an ecologically important forage fish that also have supported an economically important fishery in Prince William Sound. The herring population in Prince William Sound declined from its peak of approximately 133,000 metric tons in 1988 to 30,000 metric tons in 1993. This led to a closure of the herring fishery, which was reopened for a limited period between 1996 and 1998; however, the fishery has been below the management threshold of 22,000 metric tons since 1998 and no commercial fishery has occurred. The cause of the collapse is not agreed upon, nor is there agreement on the reasons for the lack of recovery. Several factors are thought to be involved in maintaining depressed stock levels including predation, changes in ocean conditions, salmon hatcheries, and disease.

Herring are considered an injured resource from the *Exxon Valdez* oil spill that has not recovered. Recovery of the herring population has been the focus of over 100 projects and programs funded by the EVOSTC. This has led to several syntheses of information about herring in Prince William Sound, many contributions to herring related symposia, and many individual research papers.

In 2008, the EVOSTC began developing an Integrated Herring Restoration Plan that identified the need for consolidation of the research to provide greater understanding of the factors affecting the recovery of herring in Prince William Sound. This led to the Prince William Sound Herring Survey program that began in 2009 and evolved into the HRM program that began in 2012. The work in these programs build upon the research conducted in the Sound Ecosystem Assessment program that occurred in the late 1990s. Like the Sound Ecosystem Assessment program, the Herring Survey program included examining herring but combined with research on other aspects of the ecosystem. The HRM program is focused on herring with the monitoring of other aspects of the ecosystem being included within the GWA program.

2. Overview of the special issue

Papers included in this special issue explore what we've learned thus far about persistent spill effects, environmental variability in the northern Gulf of Alaska, nearshore ecosystem variability, the lack of recovery of Prince William Sound herring, and the effect (or lack thereof) of recovering upper trophic level species on herring and other forage fishes.

2.1. Persistent spill effects

Findings from four papers presented in this issue address our current knowledge of persistence and bioavailability of *Exxon Valdez* oil in Prince William Sound.

Lindeberg et al. (2017) present findings from a lingering oil survey conducted during the summer of 2015 at a small set of beaches in Prince William Sound known to have persistent subsurface *Exxon Valdez* oil. They found little evidence of change in oil area or mass over the last 14 years, and no change in the distribution of oiling intensities and their location on the beach. Detailed analysis of the oil indicates it has not weathered since 2001. Subsurface oils collected in 2015 have enriched concentrations of phenanthrenes and chrysenes relative to oil originating in the cargo hold, indicating that buried oil has retained some toxic potential over the last two decades, but it is not currently bioavailable. Subsurface oil appears to be sequestered in sediments and protected from natural weathering processes.

Nixon and Michel (2017) refine previously presented models with additional data to characterize the present-day linear and areal spatial extent and quantity of lingering subsurface oil. Their findings estimate that lingering subsurface residues, generally between 5 and 20 cm thick and sequestered below 10–20 cm of clean sediment, are present over 30 ha of intertidal area, along 11.4 km of shoreline, and represent approximately 227 t or 0.6% of the total mass of spilled oil. Findings from both studies are consistent with previous efforts suggesting the estimated 0.6% *Exxon Valdez* oil remaining is sequestered and not bioavailable unless disturbed and will likely persist in the environment for at least another decade.

The long-term persistence of oil in the environment has presented a need for innovative ways to detect the bioavailability of oil in the environment. Standard toxicological methods to evaluate petroleum contaminants have assessed tissue burdens, with fewer assays providing indicators of health or physiology, particularly when contaminant levels are low and chronic. Bowen et al. (2017) addresses the issue by using gene-based assays of exposure and physiological function to assess chronic oil contamination using the standard key species Pacific blue mussel (*Mytilus trossulus*). They present a diagnostic gene transcription panel used to investigate exposure to polycyclic aromatic hydrocarbons (PAHs) and other contaminants and their effects on mussel physiology and health. Results show gene transcription patterns of mussels from boat harbors are consistent with elevated exposure to PAHs or other contaminants (positive control), whereas transcription patterns of mussels sampled from shorelines in areas affected by the oil spill indicate no PAH exposure.

As we approach nearly three decades since the *Exxon Valdez* oil spill we now have a better understanding of timelines and mechanisms of wildlife population recovery from the spill. Esler et al. (2017) provide an insightful synthesis of key findings from some well-studied species injured by the spill. For species such as harlequin ducks (*Histrionicus histrionicus*) and sea otters (*Enhydra lutris*), chronic oil spill effects persisted for at least two decades and were a larger influence on population dynamics over the long term than acute effects of the spill. While many seabirds experienced direct and indirect effects of the spill, population trajectories of some piscivorous birds, including pigeon guillemots (*Cepphus columba*) and marbled murrelets (*Brachyramphus marmoratus*), are linked to long-term environmental changes independent of spill effects. Another species, the killer whale (*Orcinus orca*), suffered population declines due to acute spill effects that have not been resolved despite lack of chronic direct effects.

2.2. Environmental drivers

The GWA program monitors changes in physical and biological oceanography to assess the effect of "bottom-up" changes in ocean productivity on *Exxon Valdez* oil spill injured and recovered species. This issue includes three new analyses of long-term environmental data that examine oceanographic patterns in Prince William Sound over multiple decades, interannual variability in plankton on the northern Gulf of Alaska shelf, and seasonal patterns in Prince William Sound zooplankton communities. The multi-year Pacific marine heat wave that started in coastal Alaska in late 2013 emerged as a significant driver of physical and biological changes in the analyses presented in each of these papers.

Campbell (2017) characterizes interannual and spatial variability in Prince William Sound oceanography. The analysis uses data from vertical profiles of temperature and salinity collected from 1973 to 2016 and ship and buoy observations of sea surface temperature data from 1960 to 2016, combined with long-term time series of meteorological data and upwelling indices. Results include an overall multi-decadal warming trend across the region (including a warm anomaly from 2013 onward), except cooling and freshening in surface waters of northwestern Prince William Sound from increased glacially-driven freshwater inputs. Observed long-term salinity increases in some deeper waters suggest enhanced estuarine circulation and deep-water transport. Observed shoaling of mixed layer depths over time is consistent with long-term trends in temperature and salinity, increasing near-surface water column stability.

Batten et al. (2017) characterize interannual variability in plankton concentration and community composition along two Continuous Plankton Recorder transects from the northern Gulf of Alaska shelf break to the Prince William Sound entrance (2000–2003) and into Cook Inlet (2004–2015). The analysis attributes interannual variations in plankton communities to changes in environmental conditions, particularly through the direct effect of water temperature changes on plankton metabolic processes, but also from indirect effects associated with changes in water column stability and mixed layer depth. The authors report a significant positive relationship between temperature, diatom abundance, and zooplankton biomass from

2000 to 2013, but this relationship broke down during the anomalously warm years of 2014 and 2015, indicating the potential for such climate variations to disrupt marine food webs.

McKinstry and Campbell (2017) sampled twelve locations across Prince William Sound from 2009 to 2016 to characterize annual patterns and interannual variability in zooplankton communities. They identify dominant species and use generalized additive models to demonstrate that annual peak zooplankton abundance occurs in July, with significantly higher zooplankton abundance in 2010 and lower abundance in 2013. Six distinct zooplankton communities occur in the Sound, separated by season (winter, spring/summer, fall) and location (bays, open water). Overall, the summer zooplankton community varies between years and disappeared during the anomalously warm years of 2014 and 2015, indicating a potential mechanism for how fluctuations in oceanographic conditions could affect higher trophic predators including juvenile herring.

2.3. Nearshore ecosystem

Nearshore ecosystems are dynamic and encounter numerous physical, oceanographic, and biological pressures and can be particularly sensitive to anthropogenic perturbations (Coletti et al., 2016). In the aftermath of the *Exxon Valdez* oil spill many nearshore species showed evidence of acute and chronic injury. Within this issue, two papers are focused on gaining a better understanding of northern Gulf of Alaska's nearshore ecosystem.

Konar and Iken (2017) address the challenges of monitoring marine vegetation in rocky intertidal and seagrass habitats in the northern Gulf of Alaska by testing the effectiveness of newly available technology, small unmanned aerial vehicles (sUAV). Their findings show that sUAV imagery has large-scale applicability to develop maps that show the distribution patterns and patchiness of seagrass beds. Monitoring goals or research questions that can be answered on a relatively coarse taxonomic level can benefit from a sUAV-based approach. sUAVs allow a much larger spatial coverage within the time constraints of a low tide interval which is not possible by observers on the ground. Bodkin et al. (2017) present their findings on the variation in abundance of the Pacific blue mussel in the northern Gulf of Alaska between 2006 and 2015. For all metrics monitored, mussel abundance varies on a site-by-site basis. After accounting for site differences, results show similar temporal patterns in several measures of abundance, in which abundance was initially high, declined significantly over several years, and subsequently recovered. Averaged across all sites, they document declines of 84% in large mussel abundance through 2013 with recovery to 41% of initial abundance by 2015. These findings, among others, suggest that factors operating across the northern Gulf of Alaska affect mussel survival and, subsequently, abundance.

2.4. Pacific Herring

Herring abundance in Prince William Sound varies in time and space due to a myriad of factors. The adult population migrates from the spawning grounds to summer feeding areas and on to overwintering locations. Bishop and Eiler (2017) examine the movements of adult herring in Prince William Sound by using acoustic fish tags and stationery acoustic receiving instruments. Overall, adult herring move from spring spawning grounds to the major entrances of Prince William Sound, where they remain until mid-June when they leave the Sound for the Gulf of Alaska shelf. Detections of tagged herring at Montague Strait and Port Bainbridge passages from September through early January indicate that herring schools overwinter in this area and are highly mobile, suggesting that some herring remain in the Gulf of Alaska until late winter.

Examining the use of nursery habitats by age-0 and age-1 herring, Lewandoski and Bishop (2017) find that age-0 herring remain in nursery areas throughout the winter while age-1 herring move from the inner parts of the bays towards the mouths by early spring. Preferred nursery areas are near eelgrass beds and where the salinity is lower. These herring also use seasonal ice shelves as a preferred habitat.

Gorman et al. (2017) evaluate the role of connectivity between Prince William Sound and the Gulf of Alaska in determining the energetic content of age-0 herring. A depleted δ13 C' isotope signature is associated with carbon sources in the Gulf rather than the Sound. In November, juvenile herring with a more depleted carbon isotope signature are more energy dense and found more in the northern and western portions of Prince William Sound, suggesting that intrusions of water from the Gulf of Alaska enhances the condition of age-0 herring. The results from observations in March, however, suggest seasonal variations in circulation or overwintering feeding are important in determining the energy density of age-0 herring in the spring.

Herring spawning biomass and recruitment vary over longer time scales. Sewall et al. (2017) examine the relationship between recruitment to the spawning stock and environmental variables. They find that the abundance of young-of-the-year (YOY) walleye pollock (*Gadus chalcogrammus*) is a significant predictor of herring recruitment. Years with high abundances of YOY pollock are associated with strong year classes of herring. The addition of sea temperature, primary productivity, predator abundance, and other competitor abundance does not improve the herring recruitment model. The presence of pollock may provide a prey shelter for herring or indicate oceanographic conditions favorable to juvenile pollock and herring.

2.5. Upper trophic levels

Marine birds and mammals occupy the northern Gulf of Alaska year-round and were affected directly and indirectly by the *Exxon Valdez* oil spill. As high-level predators in the northern Gulf of Alaska ecosystem, marine birds and mammals can affect the recovery of lower trophic level species impacted by the spill (e.g. Prince William Sound herring) or, alternatively, they may be affected by changes in lower trophic level species abundance and distribution. This issue includes six papers that evaluate upper trophic level species in Prince William Sound in relation to lower trophic level species and environmental variability. Two papers examine marine birds, including separate evaluations during periods of overwintering and nesting and brood rearing. The remaining papers evaluate cetaceans, including Dall's porpoise (*Phocoenoides dalli*), humpback whale (*Megaptera novaeangliae*), and killer whale.

Stocking et al. (2017) use nine winters of marine bird surveys (2007–2016) to explore piscivorous marine bird distributions in Prince William Sound outside of the breeding season and identify important criteria for winter refuge. They use hurdle models to examine nine species groups of piscivorous seabirds. Of these nine, seven groups demonstrate pronounced seasonal patterns. Model results indicate that water depth and distance to shore are key environmental covariates, while habitat type, wave exposure, sea surface temperature and seafloor slope explain less of the variation. Finding similar results during the nesting and brood rearing season, Cushing et al. (2017) document spatial and temporal patterns of variability in the Prince William Sound summer marine bird community in relation to habitat and climate variability spanning 1989–2012. Similar to results from winter surveys, an environmental gradient related to water depth and distance from shore is the dominant factor spatially structuring the marine bird community in summer. Genera associated with habitats in deeper water farther from shore experienced the greatest declines. Most of the genera that declined primarily feed on pelagic prey resources, such as forage fish and mesozooplankton. These observations of synchronous declines indicate a shift in pelagic components of Prince William Sound food webs and correlates with climate variability at timescales of several years to a decade.

Dall's porpoise are a conspicuous predator in the Prince William Sound ecosystem, yet there has been little effort directed towards studying this species since the 1980s, prior to the *Exxon Valdez* oil spill. Moran et al. (2017b) use vessel-based surveys to examine the seasonal distribution of Dall's porpoise in the waters of Prince William Sound during 2007–2015. Based on habitat analysis using generalized additive models, Dall's porpoise are found in deeper water during summer and in shallowest water during spring. The authors propose that their use of novel habitats is a function of reduced predation risk associated with the decline of their main predator, killer whales, following the *Exxon Valdez* oil spill, and the presence of overwintering and spawning herring. While the size of the Dall's porpoise population within Prince William Sound remains unknown, encounter rates are somewhat lower than those reported in the 1970s.

As North Pacific humpback whales rebound from commercial whaling, their ability to influence their prey through top-down forcing increases. Two papers in this issue examine the impact of humpback whale predation on herring and how they could be affecting the recovery of herring in Prince William Sound. Straley et al. (2017) address predation effects by comparing foraging humpback whales and their influence on three herring populations in the Gulf of Alaska: Prince William Sound, Lynn Canal, and Sitka Sound between 2007 and 2009. In Prince William Sound, the presence of whales coincides with the peak of herring abundance, allowing whales to maximize the consumption of overwintering herring prior to their southern migration. In Lynn Canal and Sitka Sound, peak attendance of whales occurs in the fall, before the herring completely move into overwintering areas, hence, there is less opportunity for predation to influence herring populations. Humpback whales in the Gulf of Alaska may be experiencing nutritional stress from reaching or exceeding carrying capacity, or oceanic conditions may have changed sufficiently to alter the prey base. Moran et al. (2017) model the biomass of herring consumed by humpback whales by estimating herring consumption in two depressed (Lynn Canal and Prince William Sound) and one robust (Sitka Sound) herring population during fall and winter, 2007–2008 and 2008–2009. Results from the model show whales remove a greater proportion of the total biomass of herring available in Lynn Canal and Prince William Sound than in Sitka Sound. Biomass removals are greatest in Prince William Sound where the largest number of whales forage on herring. The biomass of herring consumed in Prince William Sound approximates the biomass lost to natural mortality over winter as projected by age-structured stock assessments. These data indicate that the focused predation in Prince William Sound can exert top-down controlling pressure.

Killer whales are a long-lived species and have not recovered from the *Exxon Valdez* oil spill. Resident killer whales frequenting Prince William Sound area are a genetically and behaviorally distinct ecotype found in the North Pacific that feeds primarily on Pacific salmon (*Oncorhynchus* spp.). Olsen et al. (2017) investigated core use areas of resident killer whales by deploying 37 satellite tags representing 12 pods in the northern Gulf of Alaska from 2006 to 2014 and receiving transmissions between June to January each year. They identify core use areas through utilization distributions by using a biased Brownian Bridge movement model. Core use areas are highly specific to season and pod. The seasonal differences in core use may be a response to the seasonal returns of salmon, though details on specific migration routes and timing for the salmon are limited.

3. Summary

More than 25 years have passed since the *Exxon Valdez* ran aground on Bligh Reef in Prince William Sound. Through the EVOSTC, hundreds of scientific investigations have examined effects of the *Exxon Valdez* oil spill since spring 1989, making it one of the most studied oil spills globally. Through these studies, the EVOSTC and scientific community have learned a great deal about persistence of oil, differential responses of species to acute and chronic exposure to oil, and the role of ecosystem variability in understanding species recovery. Some species have not yet recovered and continued long-term monitoring through the GWA and HRM programs will result in greater understanding of Gulf of Alaska ecosystems and their road to recovery.

Contrary to initial expectations after the spill, some impacts have persisted for decades. Currently, experts know the oil persists in subsurface patches, its chemical composition, and projected distribution and quantity in Prince William Sound. There are now new ways of detecting bioavailability of low-level petroleum contaminants in the environment by looking at gene transcription patterns in marine organisms. Finally, after decades of tireless research by many devoted scientists, experts can look back and understand how wildlife populations were damaged, as well as the mechanisms and timelines of their recovery, and the context of oil spill injury relative to other sources of variation.

Variability in oceanographic conditions in the northern Gulf of Alaska have made investigation into species recovery from the *Exxon Valdez* oil spill difficult. Varying environmental drivers, El Niño, and the recent heat wave exemplify the complexities of the Gulf of Alaska ecosystem and continue to influence species pathways to recovery. Adding to the puzzle are predator-prey interactions such as bottom-up effects on herring and other forage fish and top-down pressures from marine birds and mammals. Marine bird and mammal species injured by the spill have demonstrated highly variable rates of recovery based on the nature of their injury and their life histories, including what they eat and where they find their prey.

The pathway to recovery for Pacific herring is one that has not been resolved. The crash of the Prince William Sound herring population following the *Exxon Valdez* oil spill and lack of recovery after nearly three decades remains among the most complex ecological enigmas in the northern Gulf of Alaska. Their status as a forage fish in the center of the ecological food web means they are potentially directly affected by bottom-up pressures from changing oceanographic conditions and top-down pressures from recovering populations that feed on herring.

The story of recovery from the *Exxon Valdez* oil spill and findings of the first five years of the GWA and HRM programs demonstrate the need for long-term monitoring and research to distinguish anthropogenic impacts from natural variability, especially given the frequency and longevity of natural cycles in the Gulf of Alaska. Furthermore, studying ecosystems through multiple cycles of variability is critical to understanding mechanisms of change and future implications for marine resource management and recovery of injured species. Future synthesis publications from the GWA and HRM programs will seek to resolve currently unanswered questions about species injured by the spill in an ecological context.

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