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FINAL
LONG-TERM EFFECTS AND LOCATION OF LINGERING OIL FROM THE EXXON VALDEZ OIL SPILL IN PRINCE WILLIAM SOUND

LITERATURE REVIEW

Prepared for

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ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
µg/L	micrograms per liter
ADEC	Alaska Department of Environmental Conservation
cm	centimeters
DWH	Deepwater Horizon
EROD	7 ethoxyresorufin-O-deethylase activity
EVOS	*Exxon Valdez* Oil Spill
EVOSTC	*Exxon Valdez* Oil Spill Trustee Council
GIS	geographical information systems
GWA	Gulf Watch Alaska
ha	hectares
HOR	Heavy Oil Residue
HSOS	Hebei Spirit oil spill
kg	kilograms
kg/m2	kilograms per square meter
km	kilometers
LOR	Light Oil Residue
MNA	monitored natural attenuation
MOR	Medium Oil Residue
msl	mean sea level
OF	Oil Film
PAH	polycyclic aromatic hydrocarbons
PWS	Prince William Sound
RCAC	Regional Citizens Advisory Council
RT-qPCR	reverse transcriptase quantitative polymerase chain reaction
TEK	traditional ecological knowledge
tPAHs	total polycyclic aromatic hydrocarbons
VHSV	viral hemorrhagic septicemia virus

1. INTRODUCTION

The *Exxon Valdez* oil spill (EVOS) occurred on March 24, 1989 in Prince William Sound (PWS). An estimated 11 million gallons of oil were spilled in PWS, yet only 10% of the total oil spill was recovered by cleanup efforts[1]. Since then, hundreds of scientific investigations have looked at the long-term fate, transport, and effects of the EVOS on the ecological communities of PWS. More than 30 years of research has provided a great deal of information on the persistence of oil and the responses of different species to both acute (short-term) and chronic (long-term) effects of exposure to oil, as well as the role the ecosystem plays in the recovery of affected species.

Figure 1. Lingering oil found on July 8, 2021, at the northwest bay of Eleanor Island.

Photograph taken and provided by David Janka.

At the time of the EVOS, only approximately 10% of the released oil was recovered from beaches and surface water. During the last 30 years, much of the unrecovered oil has disappeared due to natural processes. For example, microorganisms that can degrade oil exist in all marine environments, including cold, deep, and high-pressure settings[2]. Often on oiled shorelines, natural levels of nutrients are insufficient for degradation of larger oil spills—which is why approximately 50,000 kilograms (kg) of nitrogen and 5,000 kg of phosphorous were applied to oiled shorelines in PWS[2]. Despite the action of natural processes and cleanup efforts, a portion of the initial EVOS oil spill persists in the aquatic environment as sequestered subsurface oil and surface oil patches (Figure 1).

Since the EVOS, the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) has executed multiple projects focusing on the long-term fate and transport of lingering oil and long-term monitoring of marine conditions and injured resources, harbor protection and marine restoration, and habitat acquisition and protection. The Alaska Department of Environmental Conservation (ADEC) reviews information regarding the presence of subsurface lingering oil and has listed several beaches as impaired due to lingering oil. These lists were last updated in 2015. The objectives of this project are to review recent EVOS literature (2015 to present) to determine which areas in PWS may have lingering oil and to produce a summary of the available resources and data that could be used to evaluate the nature, extent, and effects of lingering oil. In addition to this document, a GIS database was developed to provide location information for the lingering oil locations in the studies revised in this annotated bibliography. Additionally, studies that discuss species that were injured by EVOS (harlequin duck, sea otters, Pacific herring, etc.), and

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[1] NOAA: https://oceanservice.noaa.gov/podcast/mar14/mw122-exxonvaldez.html

[2] Hazen and Prince. 2015. Marine Oil Biodegradation. ES&T. DOI: 10.1021/acs.est.5b03333

traditional ecological knowledge (TEK) resources/sources were included, with the overall goal of providing updated information on the lingering oil's nature, extent, and impacts to stakeholders.

2. METHODOLOGY

To conduct the literature review and develop this annotated bibliography, experts on lingering oil in Alaska were interviewed to identify key resources, reports, and studies to include in the literature review. Additionally, these interviews provided insights into how experts from different agencies and sectors studying the effects of lingering oil in PWS think about the subject. After interviews, available resources were initially screened to reduce the list to 50 relevant documents, which were further refined to the 25 most relevant documents included in the annotated bibliography. This section provides details on the interview and literature review methods.

2.1 Lingering Oil Expert Interviews

Initially, the literature review process consisted of interviewing experts on lingering oil in PWS. David Janka (PWS Regional Citizens Advisory Council [RCAC] board member), Jackie Keating (subsistence resource specialist for PWS), Morgan Bender (ecotoxicologist working on long-term environmental monitoring project on hydrocarbons in PWS), and Sarah Allan (ecotoxicologist with the National Oceanic and Atmospheric Association [NOAA]) were interviewed virtually, while Roger Prince (lead scientist for the monitoring program following EVOS, Exxon Mobil) provided responses to questions via email. Experts were asked the series of questions given below, and meeting notes were submitted to ADEC on August 1 and September 7, 2023:

- What research have you been involved in regarding lingering oil (bioavailability, impacted resources, etc.)?
- What literature is important for us to include?
- Have you been involved in traditional knowledge studies regarding lingering oil, and if so, where can we find those results?
- Is there any other relevant research that you know about that isn’t published (current or newly completed studies)?
- Are there any geographical information systems (GIS) resources that you have or know about?
- Are there research data gaps related to lingering oil?
- Is there anything else that you would like us to know as we complete this literature review?
- Are you interested in receiving project updates through a listserv? If so, please provide a good contact email.

2.2 Literature Review and Screening

To be exhaustive, the EVOS portal[3] was queried for documents published since 2015, which resulted in an initial return of 301 projects and reports. These reports were then reviewed to identify and exclude projects or reports that were not relevant to the study objective (such as budget reports, project management files, etc.). Additionally, projects that were listed but did not have a final report available were also excluded. The initial 301 reports were thinned to 25 documents relevant to the goals of this review for the initial screening.

In addition to these files from the EVOS portal, Google Scholar and Pubmed were searched with terms relevant to the project, such as “lingering oil Alaska,” “Prince William Sound,” etc., and these searches resulted in an additional seven peer reviewed journal articles. Twenty peer-reviewed journal articles published in the 2018 special issue of the *Deep Sea Research Part II* were also included in the initial screen.

Based on expert interviews, seven documents were identified as critical to the review. Critical documents included reports from the EVOS portal, studies from the *Deep Sea Research Part II* special issue, and reports from the Alaska Department of Fish and Game. Combined, an initial 53 peer-reviewed journal articles and/or reports were identified for preliminary consideration.

Each of the 53 articles and/or reports was reviewed to identify and summarize the following information (Table 1): author name, year, study name, type of study, locations of study, injured species, recovered species, and type of document. Table 1 also captures whether the study provides recent chemistry, bioavailability, and/or toxicological data, discusses socioeconomic aspects, provides methodology, raw data, geospatial data or maps, or seasonality data, and identifies if the document was recommended by one of the interviewed subject matter experts. Finally, the table includes a link to the study and study data (if available), general notes, and an internal ranking of how useful this study is expected to be to the scope of the project.

2.3 Annotated Bibliography

The initial 53 documents were reduced to the 25 most relevant to the project by evaluating each paper for inclusion of relevant species, data and those recommended by experts. Projects that have recent data as well as geolocations of lingering oil were prioritized. Following discussion and concurrence with ADEC, these 25 documents were reviewed and summarized in the annotated bibliography provided in Section 3. The annotated bibliography is organized into the following sections: nature and extent of lingering oil, ecological impact, and socioeconomic/TEK effects.

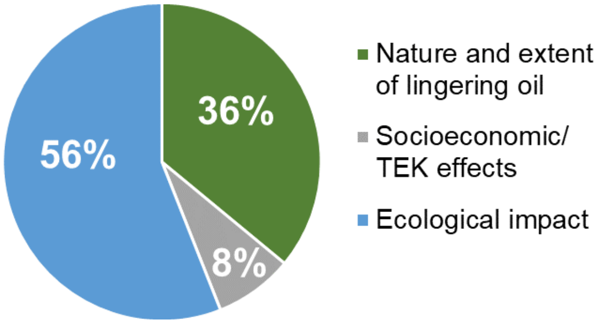

Figure 2. Breakdown of the 25 annotated bibliographies by section and percent.

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[3] https://evostc.state.ak.us/restoration-projects/project-search/

The majority (56%) of reports since 2015 were focused on ecological impacts, while the nature and extent of lingering oil and socioeconomic/TEK effects were a smaller proportion (Figure 2). For the ecological studies since 2015, the majority of studies were focused on Pacific herring, marine invertebrates, and marine birds (Figure 3). The annotated bibliographies are organized alphabetically by author; they present an overview of each study, methodology, and key results as presented by study authors.

It should be noted that the conclusions presented within this report are those presented by the authors of the papers that were reviewed. Geosyntec Consultants, Inc. has not provided additional validation of any results or conclusions.

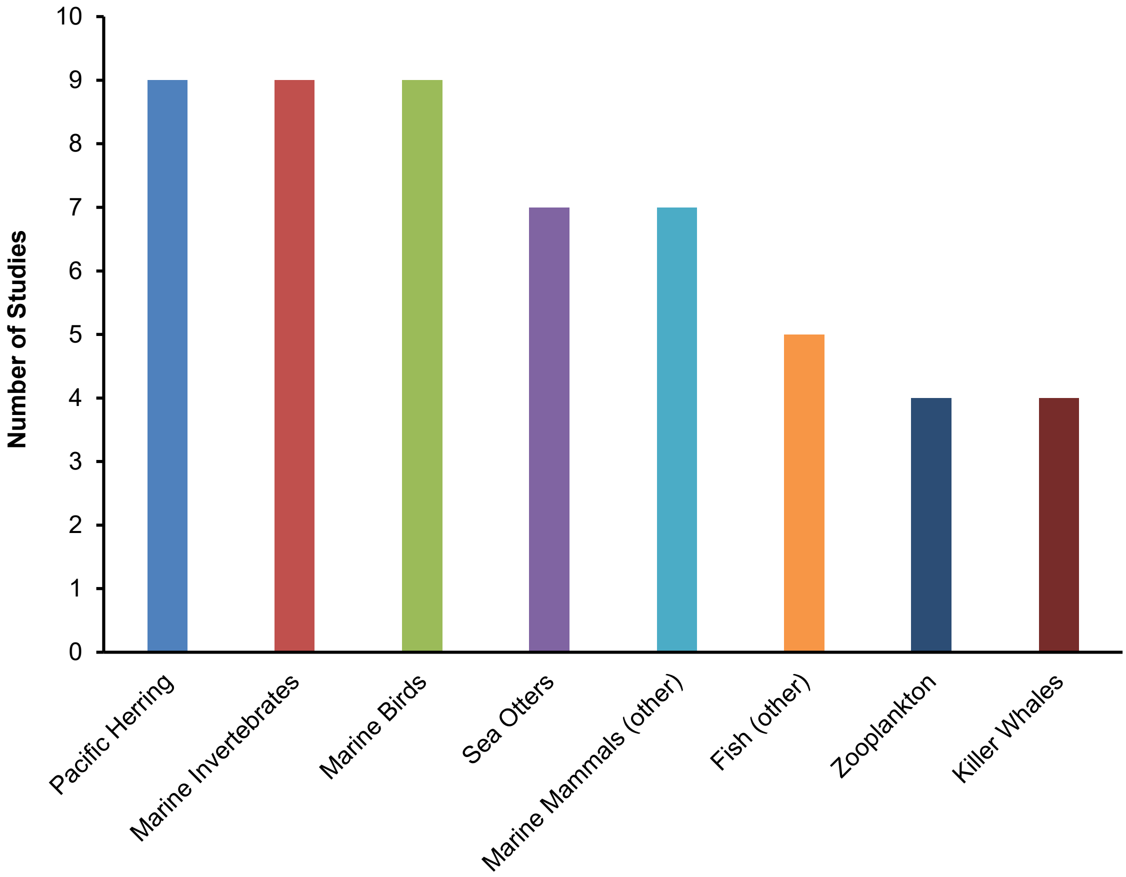

Figure 3. Number of studies/reports that included monitoring data or studies on each group of animals.

2.4 Geospatial Data Assembly (GIS mapping tool)

Of the 50 studies originally selected for this study, 16 contained map figures, and 3 of those 16 also had direct access to digital geospatial data. Many studies reference the same lingering oil field observation datasets and add new observations to existing datasets. In light of this, we targeted and retrieved geospatial data from Boufadel et al. (2015). This dataset contains most field observed (Michel et al. (2010)[4], Short et al. (2004)[5]) and modelled beach locations referenced by all the other studies. The field observations reported in Boufadel et al (2015) are from 2001, 2003, 2007, and 2008. Heintz et al. (2023) contained more recent (2015 and 2021) observations of 9 existing sites in the Boufadel et al. (2015) dataset. The retrieved data only contained observations from 2015. The2021 data were digitized from the pdf figures. Most maps from the 16 studies were either not relevant to locating lingering oil on beaches (for example, maps of herring genome sampling locations) or were not easily georeferenced (for example, Short et al. (2023) contains a figure indicating lingering oil on beaches but does not provide the data).

Each of the 16 articles and/or reports with figures/geospatial data were reviewed to identify and summarize the following information (Table 2): author name, year, study name, GIS data available, contains map (pdf), if the geospatial data was extracted for this report, dataset size and quality. The table also includes notes on the dataset and indicates whether the study is useful for impaired beaches categorizing. Finally, the table includes a link to the study and study data (if available).

The geospatial dataset assembled from the studies and interviews includes field observations of 273 shoreline segments with a total of 12,370 subsurface pit descriptions, 9 updated pit descriptions, 45 modeled shoreline segments with high probability of containing subsurface oiling of MOR or greater, and two georeferenced pictures of surface oil from a subject matter expert (David Janka). Figure 4 shows an overview of the dataset. The length of beach derived from the geospatial data of this study is not an estimate of the total length of beach that is clean or oiled in PWS. Rather, these values reflect the length of beach for each category that have digital geospatial data and were readily retrievable.

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[4] Michel, J., Z. Nixon, M.O. Hayes, J. Short, G. Irvine, D. Betenbaugh, C. Boring, and D. Mann (2010), Distribution of subsurface oil from the Exxon Valdez oil spill. Exxon Valdez Oil Spill Restoration Project Final Report (Restoration Project 070801), National Oceanic and Atmospheric Administration, Juneau, AK. 121 pp. + app.

[5] Short, J.W., M.R. Lindeberg, P.M. Harris, J.M. Maselko, J.J. Pella, and S.D. Rice (2004), Estimate of oil persisting on the beaches of Prince William Sound 12 years after the Exxon Valdez oil spill, Environmental Science & Technology, 38(1), 19-25.

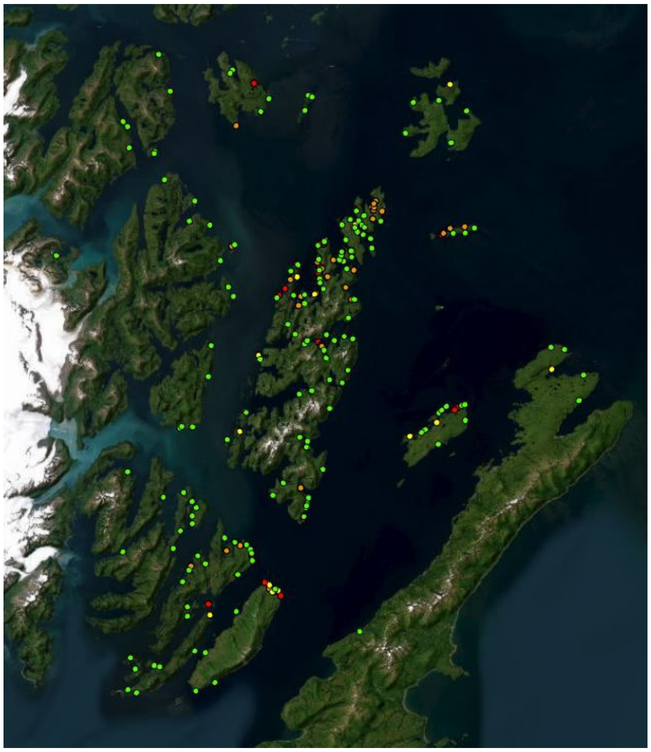
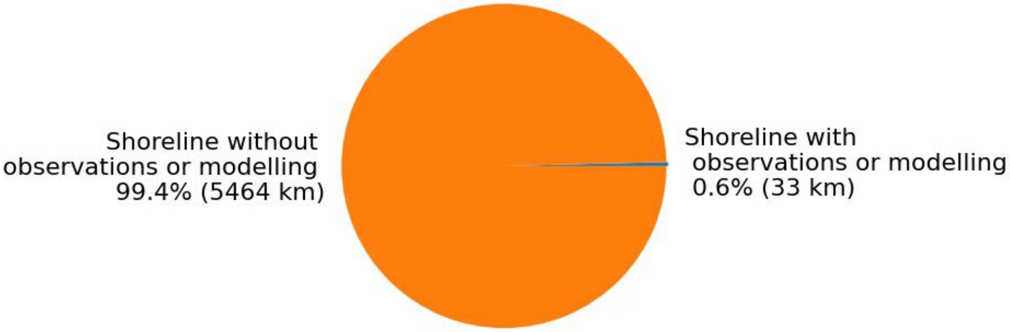


Figure 4. Overview of dataset in Prince William Sound. Green circles indicate no oil observed, yellow: surface oil observed, orange: subsurface oil observed, and red: surface and subsurface oil observed.

This data has been compiled into a geodatabase attached to this submittal. The geodatabase is compatible with ESRI ArcGIS software. The provided geodatabase has feature classes to display shoreline field observations symbolized by their categorized oiling (clean, surface oiling, subsurface oiling, and surface/subsurface oiling), modelled shoreline with MOR or greater subsurface oiling, ADEC existing 4B impaired beaches, and geotagged photos.

The total lengths of beach represented by each category are: clean (13.0 km), subsurface oil (2.9 km), surface oil (1.6 km), and surface/subsurface oil (3.3 km). Additionally, modelling has suggested that 12.0 km of beach contains moderate or heavy levels of subsurface oiling. Total shoreline in Prince William Sound is approximately 5497 km. Figure 5 shows the small fraction of shoreline in PWS that this dataset covers and also displays the percentage that each oiling category represents within this subfraction.



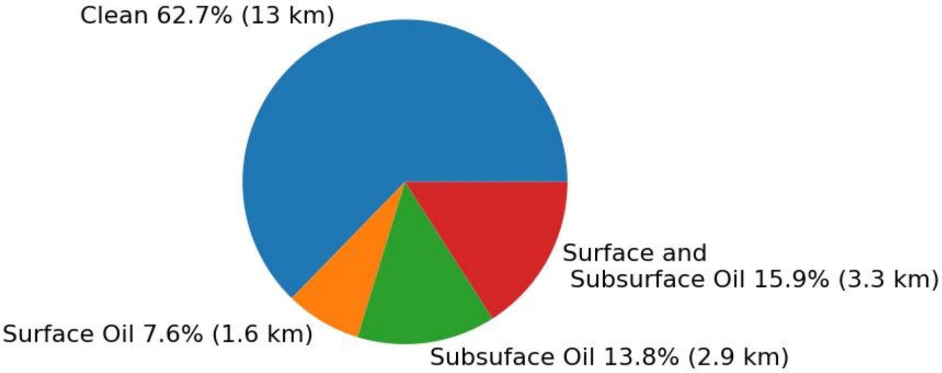
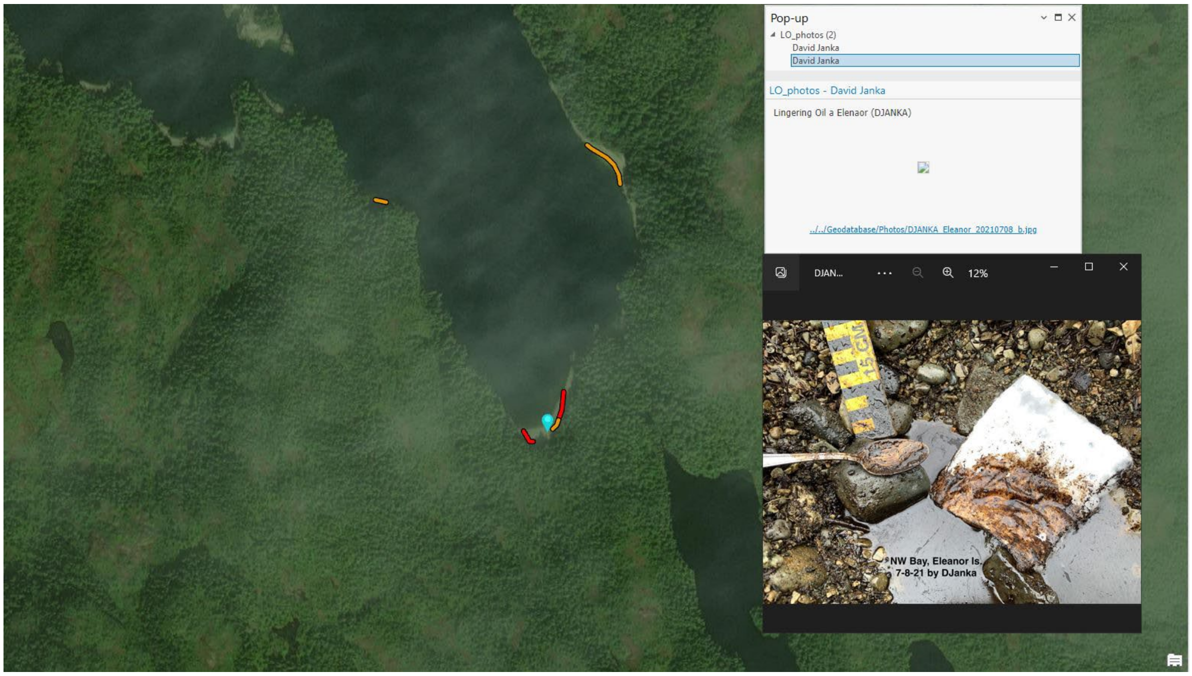


Figure 5. (Top) Percentage of shoreline within Prince William Sound that the geodatabase has observations or modeling results for. (Bottom) Representation of each oiling category within the 0.4% subfraction of shoreline that the geodatabase has field observations for. The remaining 0.2% of shoreline is modelled to have MOR or higher subsurface oiling.

Attachment A shows the schema for the geodatabase and definitions for the attributes of each feature dataset/class. Additionally, the geodatabase indicates whether a given shoreline segment is already included in the ADEC 4B impaired beaches. Fifty-four (54) of the 273 field sites were collocated with ADEC 4B impaired beaches. Modeled shoreline segments are symbolized and named “unique” or “adjacent” depending on whether they are near field observations.

Two photos of observed surface oil on Eleanor Island from are plotted as a point layer feature class and are hyperlinked with the ability to view them within the map (David Janka) (Figure 6).



Lingering Oil a Elenaor (DJANKA)

../../Geodatabase/Photos/DJANKA_Eleanor_20210708_b.jpg

Figure 6. Hyperlinked photo of surface oil on Eleanor Island (David Janka). Opened by clicking hyper link in ArcGIS or Google Earth kmz.

3. ANNOTATED BIBLIOGRAPHY OF STUDIES

3.1 Nature and Extent of Lingering Oil

3.1.1 Aderhold et al. (2018): Spatial and Temporal Ecological Variability in the Northern Gulf of Alaska: What Have We Learned Since the Exxon Valdez Oil Spill?

The document by Aderhold et al. (2018) is a summary of the 20 papers published within the special issue for *Deep-Sea Research Part II*. This issue summarizes the findings for the long-term EVOSTC project focus areas, which include effects on Pacific herring, nature and extent of lingering oil, long-term monitoring of marine conditions and injured resources, harbor protection and marine restoration, and habitat acquisition and protection.

Pacific herring was an economically important fishery in PWS that experienced a population collapse in 1993 and has not recovered since. The exact cause of the population collapse is still not agreed upon, nor are the reasons for the lack of recovery; however, factors thought to impede population recovery include predation, changes in ocean conditions, salmon hatcheries, and disease. Recovery of the herring population has been the focus of over 100 projects/programs funded by EVOSTC; however, the Pacific herring is still listed as an injured species.

Surveys conducted in PWS during the summer of 2015 indicate there is little evidence of change in subsurface oil area or mass over the last 14 years, and no change in the distribution of oiling intensities. Analysis of the oil has shown a lack of weathering since 2001. Furthermore, subsurface oils have higher concentrations of phenanthrenes and chrysenes, which indicates that the subsurface oil has the potential to be toxic, but the lack of weathering suggests that the oil is sequestered in the subsurface. Mathematical modeling suggests that lingering subsurface oil is typically sequestered below 10-20 centimeters (cm) of clean sediment and is located over 30 hectares (ha) of intertidal area and 11.4 kilometers (km) of shoreline, which represents about 0.6% of the total mass of the original spilled oil from EVOS. This sequestered oil is not bioavailable unless disturbed and is predicted to persist in the environment for at least another decade.

Marine conditions were also monitored, with the Pacific marine heatwave from 2013–2016 acting as a significant driver of physical and biological changes to animals in the Gulf of Alaska, including PWS. The Pacific marine heatwave has been associated with a disruption of marine food webs via a reduction of primary producers and prey fish. These changes to marine conditions could be impacting the ability of injured prey fish, such as juvenile Pacific herring, to recover.

3.1.2 Boufadel et al. (2015): Priorities, Methods, and Costs for Restoration of Lingering Subsurface Oil from the Exxon Valdez Oil Spill in Prince William Sound, Alaska

The study by Boufadel et al. (2015) identifies EVOS lingering oil sites in PWS and discusses potential techniques and expenses for restoration of priority sites. Sites were identified using data collected in field surveys from 2001–2014, and potential sites were identified from a model developed in 2015. The sites identified through field survey data were divided into four categories based on subsurface oiling condition (Exhibit 1).

Exhibit 1. Table 1 from the report by Boufadel et al. (2015), reproduced with slight modifications for this report. Site categorization based on subsurface oiling conditions for sites in 2001-2014 field surveys.

Category	**Description**
Oil Film (OF)	Continuous layer of sheen or film on sediments
Light Oil Residue (LOR)	Sediments lightly coated with oil residue; pore spaces not filled with oil or oil residue
Medium Oil Residue (MOR)	Heavily coated sediments; pore spaces not filled with oil or oil residue
Heavy Oil Residue (HOR)	Pore spaces partially (or completely) filled with oil or oil residue; oil may or may not flow from pore spaces

Field survey sites were selected as priority sites if subsurface oiling intensities classified as MOR or higher were observed at one or more pits. The model output also ranked locations from most likely to least likely to have an oiling intensity of MOR or greater using existing field data, along with geological and hydrological factors. Modeled sites were further classified as either adjacent to sites previously investigated in the field (within 100 meters) or as unique sites (> 100 meters). A list of sites (both field and model-predicted) was generated after applying the criteria; the sites were then mapped. After mapping, additional miscellaneous screening criteria were used to remove sites from consideration, such as sites with an oil thickness of 5 cm or less, known sites with total polycyclic aromatic hydrocarbons (tPAH) concentrations below 44 parts per million (ppm), sites with a shallow peat area, and sites that were difficult or dangerous to access. Model sites adjacent to field sites that were removed from consideration were also removed, and unique model sites where the estimated area of MOR oiled sediments was equal to or less than 20 square meters were removed.

The final list included 63 candidate sites, with 40 known field sites, 18 adjacent model-predicted sites, and 5 unique model-predicted sites. The volume of sediments to be treated was estimated for all sites with field site sediment volumes estimated by multiplying the area coverage by oil thickness, where adjacent model sites used the oil thickness of the closest site in the estimate, and unique sites used a default oil thickness of 15 cm. Known sites with the highest estimated volume of sediment for restoration were located in Herring Bay (20.4 cubic meters) and Smith Island (36.1 cubic meters). The highest volumes for model-predicted adjacent sites were three sites along Smith Island (51.7-55.5 cubic meters), and the model-predicted unique site with the highest volume was along the shore of Eleanor Island (62.5 cubic meters).

Three restoration options were considered for each site: monitored natural attenuation (MNA), manual labor techniques, and bioremediation techniques. Feasibility for each one of these options was evaluated by looking at the degree of intrusiveness, cost, and achievable endpoints. MNA, or “natural recovery,” was both lowest in cost and the least intrusive remedial method considered, and is a useful method at sites where further treatment would cause significant disturbance. MNA can reduce the exposure of ecological receptors to oil, and monitor the levels of tPAHs (the most toxic component within oil) until they drop below acceptable threshold levels via natural processes, but does not reduce overall oil mass. Bioremediation involves annually injecting amendments into oil-polluted sites to reduce tPAH concentrations. Bioremediation can be costly depending on the number of injections and amendments, and there are multiple site-specific factors that need to be considered before this method is applied. Manual labor is the process of physically removing oiled sediments. However, this method is highly intrusive, as it involves excavating clean overlying sediment to reach the layer of oiled sediment. Oiled sediment is then removed and cleaned and returned to the excavated area. Boufadel et al. (2015) evaluated the feasibility of these three techniques on a site-by-site basis and assigned a recommended technique to each of the 63 sites. In addition, the specific costs for different restoration scenarios were estimated.

3.1.3 Bowen et al. (2018): Gene Transcription Patterns in Response to Low Level Petroleum Contaminants in *Mytilus trossulus* from Field Sites and Harbors in Southcentral Alaska

Bowen et al. (2018) used a gene-based assay of exposure and physiological function to assess if Pacific blue mussels (*Mytilus trossulus*) are being impacted by chronic oil spill contamination in PWS. Mussels were collected in 2012–2015 from sites in five embayments in western PWS with varying oil histories from EVOS (Herring, Hogan, Iktua, Johnson, and Whale), as well as three boat harbors in the area (Cordova, Whittier, Seward). The five sites in western PWS represent 3,000 square kilometers and were all within the area of EVOS. All mussels were collected on the morning rising tide, sampled as soon as possible (less than 1 hour), preserved in RNAlater, and analyzed following standard reverse transcriptase quantitative polymerase chain reaction (RT-qPCR).

Gene expression analysis revealed that the three harbors had elevated expression of genes related to PAH exposure (Cyp3, Casp8 and CCOIV), while none of the five sites in PWS did. There was no significant difference in gene expression between the five PWS field sites, which was notable since the five field sites were exposed to varying degrees of oiling during EVOS (Whale and Johnson Bays received very little oil, Iktua and Hogan bays were moderately oiled, and Herring Bay was heavily oiled). Bowen et al. (2018) suggest that it is possible that lingering oil at the sites may have been sequestered and undisturbed in the sediments prior to sampling and thus not biologically available to mussels. An alternate hypothesis presented in this paper is that lingering oil may have been reduced or degraded to inconsequential levels. Although not related to lingering oil, the study also measured genes indicative of ocean acidification, which were elevated in 2012 relative to other years. The conclusion from this study is that mussels from the boat harbors have gene transcription patterns consistent with elevated exposures to PAHs while the transcription patterns of mussels sampled from shorelines in areas affected by the oil spill indicate no PAH exposure.

3.1.4 Heintz et al. (2023): Extending the Timeline for Lingering Oil in Prince William Sound

Heintz et al. (2023) present data from a 2021 survey of five beaches in PWS to quantify remaining oil and compare 2023 survey results to previous surveys. Beaches were selected for the 2021 survey based on the 2015 survey, with beaches with the highest probability of encountering oil selected and evaluated using methods comparable to those used in previous studies (Lindeberg et al. 2018, reviewed below). Briefly, these methods included establishing a survey grid through a random stratified sampling scheme, randomly selecting pit locations, excavating the pits, assessing the pits for presence and intensity of oil, and collecting samples. Samples were not chemically analyzed for this study but were archived for future analysis. Statistical analysis was then conducted to determine the probability of encountering oil, estimate the area of oil, calculate retention rate since 2015 survey, evaluate vertical distribution, and assess frequency of residue classifications.

Subsurface oil was present at all five beaches surveyed in 2021, and oil encounter rates were slightly lower but not statistically different from those reported in 2015. The estimated proportion of oil retained between 2015 and 2021 ranged from 0.77 to 0.96, which suggests oil is not degrading on beaches, despite an observed decrease in the estimated oiled area. In addition, spatial distribution of oil and the distribution of oil types were aligned with the results obtained in the 2015 study. Therefore, the decrease in estimated oiled area is the only evidence for an overall reduction in the presence of oil, which authors indicate is likely related to the high variability involved with oiled area estimates due to small sample size (only two pits dug per block), resulting in inaccurate model estimates.

This study concludes there is no evidence of weathering, despite the reduction in oiled areas. Oil is removed through either physical factors or microbial degradation, and the lack of change in vertical distribution suggests beach armoring and other geomorphic features are sequestering oil by reducing the effects of wave action. Microbial degradation, on the other hand, is limited by the low dissolved oxygen levels found within subsurface layers of oiled beaches in PWS. Overall, oil persists on the beaches of PWS decades after the EVOS spill and will unlikely be weathered or mobilized without an anthropogenic disturbance or an unnatural event. However, evidence also suggests the sequestration of the remaining oil by beach armoring results in the oil being minimally bioavailable.

3.1.5 Lindeberg et al. (2018): Conditions of Persistent Oil on Beaches in Prince William Sound 26 Years after the Exxon Valdez Spill

Lindeberg et al. (2018) conducted a lingering oil survey in 2015, with the objectives of estimating how much oil remains at these sites, the oil composition, and oil retention rates compared to previous studies. The survey targeted nine beach segments that had previously been identified as containing persistent subsurface oil, and prioritized segments of the beach based on moderate to heavy initial oiling, previous surveys with recent observations of subsurface oil, shore type prone to armoring, and model predicted areas of lingering oil. Islands surveyed included Smith, Eleanor, Latouche, Green, Evans, and Knight Islands.

Methods for surveying beach segments, discovering oil, and estimating oiled area were based on the stratified random sampling method used during Alaska Fisheries Science Center's Auke Bay Laboratories' 2003 and 2005 lingering oil surveys to allow for comparable results. Generally, surveys included a stratified random sampling design along 100 meter segments of beach shorelines beginning at + 4.8 meter tide height and extending to down to −0.2 meter tide height. Sampling quadrats (0.25 square meters) were randomly located along the segments, resulting in 50 quadrats per 100 meters of shoreline, and were then excavated down to 0.5 meters or refusal (if encountered). Representative samples of subsurface oil were collected from each pit when encountered. Additionally, all excavated material was collected, weighed, homogenized, and subsampled for gravimetric analysis. In the laboratory, the oil volume per excavated area was determined, and oiled sediment samples were analyzed for oil source, tPAHs, and weathering state. PAHs, alkanes, and biomarkers were analyzed to determine the extent to which weathering had occurred since previous surveys.

The survey identified lingering subsurface oil at eight of the nine beaches surveyed and 11.75% of the 400 excavated pits; oil was not observed on one segment of Evens beach. Of the 400 pits excavated, 19 were identified as LOR compared with 12 MOR and 8 HOR, consistent with previous surveys from 2001 to 2007. Oil mass per unit area averaged 0.2 ± 0.2 (mean ± standard deviation) kilograms per square meter (kg/m^2) in LOR, 1.0 ± 0.3 kg/m^2 in MOR and 2.0 ± 1.0 kg/m^2 in HOR residues. Also consistent with previous surveys, the oil was primarily located in the middle of the intertidal zone with approximately equal amounts of oil located above and below.

Oil areas and weights were estimated for comparable beach segments surveyed in 2005, showing little change in subsurface oil estimates. Minimal change in the weathering state of oil was observed since previous surveys. Similarly, the probability estimates for encountering subsurface oil showed little evidence that oil had been lost from the beaches and were consistent with earlier geomorphic model predictions for persistent subsurface oil. Overall, the study shows the estimated area and mass of subsurface oil, weathering, oiling intensities, and oil locations have not changed since the surveys conducted in 2001.

3.1.6 Lindeberg et al. (2018): Lingering Oil: Extending the Tracking of Oil Levels and Weathering (PAH Composition) in Prince William Sound through Time

Lindeberg et al. (2018) conducted a project with the goals of assessing the quantity and chemical characteristics of lingering EVOS oil in PWS as well as establishing a routine for future monitoring of persisting oil. Nine sites within PWS where oil is known to persist were surveyed to quantify the amount of oil remaining and the weathering state of the remaining oil. Additionally, hydrocarbons were analyzed with a retrospective oil chemistry analysis. Chemical analysis looked at PAHs, alkanes, and biomarkers and compared them to previous sample collections to determine the weathering state of the remaining subsurface oil and to confirm EVOS as the source of the oil. Passive samplers were also deployed, and these were used alongside sediment samples to determine the bioavailability of PAHs at the sites investigated.

The surveys at PWS revealed the presence of subsurface oil with little evidence of change in weathering state. The area and weight of the oil from the 2015 surveys showed little change compared to 2001, and retention rates show oil loss is undetectable. Distribution of oil on beaches also showed minimal change, and removal rates have slowed to close to zero. It was concluded that natural weathering of the oil will not be responsible for any additional loss of oil, and that any additional loss of oil can likely be attributed to disturbance of oiled areas.

Biomarker patterns for oil samples from the past 23 years at contaminated PWS sites matched oil from the EVOS spill in 77% of samples. When looking at the composition of subsurface oil from the 2015 survey, concentrations of phenanthrenes and chrysenes indicate oil retaining potential toxicity despite being sequestered for two decades. Compounds responsible for acute toxic effects (benzene, toluene, ethylbenzene, xylene) were not present within the subsurface oil, but chronic toxic effects from PAH exposure are still possible. Despite the potential for chronic toxicity from remaining oil, results from passive samplers indicate low exposure to oil at the sediment surface, and the oil within the sediment is isolated from the environment. Low exposure to waves, beach armoring, and protective geomorphic features are all features that play a large role in the sequestration of the oil, which contributes to its persistence and lack of bioavailability.

3.1.7 Michel et al. (2016): Studies on Exxon Valdez Lingering Oil: Review and Update on Recent Findings

Michel et al. (2016) reviewed and summarized studies centered around lingering oil from the EVOS to determine the quantity and distribution of lingering oil and the effects it has on biota and subsistence use and harvest of ecological resources. Potential remedial options for remaining lingering oil were also investigated and discussed.

Subsurface lingering oil surveys conducted in 2001 found subsurface oil at 42 of the 91 beaches investigated and estimated the mass of oil remaining to be 55,600 kg. A follow-up study determined the area of oil had not significantly decreased between 2001 to 2005, with an estimated rate of decline of approximately 4% per year. Additional surveying was completed in 2007, and the data from all surveys (2001–2007) was combined to reveal the presence of subsurface oil at 88 of 307 beach segments investigated in PWS, with an average thickness of 4.1 to 20.7 cm. Variation in the degree of oil between beach segments was attributed to several factors, which are summarized in Table 1 from Michel et al. (2016) (Exhibit 2).

Exhibit 2. Table 1 from the report by Michel et al. (2016), modified slightly for this report. Hydrologic and geomorphic factors influencing the presence/absence of subsurface oil.

Factors that Increase the Likelihood of Subsurface Oil	Factors that Decrease the Likelihood of Subsurface Oil
Heavy or moderate initial oiling	Impermeable bedrock
Low exposure to wave action	Platforms with a thin sediment veneer
Low topographic slope	Fine-grained, well-sorted gravel beaches with no armor
Armoring of gravel beaches	Low-permeability, raised bay-bottom beaches
Tombolos or natural breakwaters	Proximity to a stream outlet or strong shallow groundwater flow
Rubble accumulations	
Transitional edge effects (transitions between permeable and impermeable shoreline types)	

A study in 2015 resampled six beach segments in PWS utilizing the same methods as the survey conducted in 2001 and found no change in the in subsurface oiling area or intensity. When looking at weathering, the degree of weathering between the years of 2005–2014 for subsurface oil was found to vary dramatically. Additionally, a study done in 2013 concluded that the subsurface oil in PWS does not appear to be bioavailable unless physically disturbed. While the subsurface oil may not be readily bioavailable, a study in 2010 estimated it would be decades before the remaining mass of oil is completely removed by natural processes such as microbial degradation. The rate of microbial degradation is limited by low dissolved oxygen levels in beach groundwater within the oiled areas.

The duration of exposure and resulting effects to marine invertebrate, fish, marine birds, and other wildlife were also discussed. The organisms inhabiting intertidal areas are considered the most vulnerable to lingering oil exposure, especially filter-feeding marine invertebrates living within or in close proximity to the sediment, and marine birds and mammals that regularly consume these invertebrates. Evidence from previous studies indicates harlequin ducks and sea otters face long-term exposure to lingering oil and a delayed recovery due to the chronic effects. The timeline for chronic effects and recovery of different species is depicted in Figure 11 of Michel et al. (2016) (Exhibit 3).

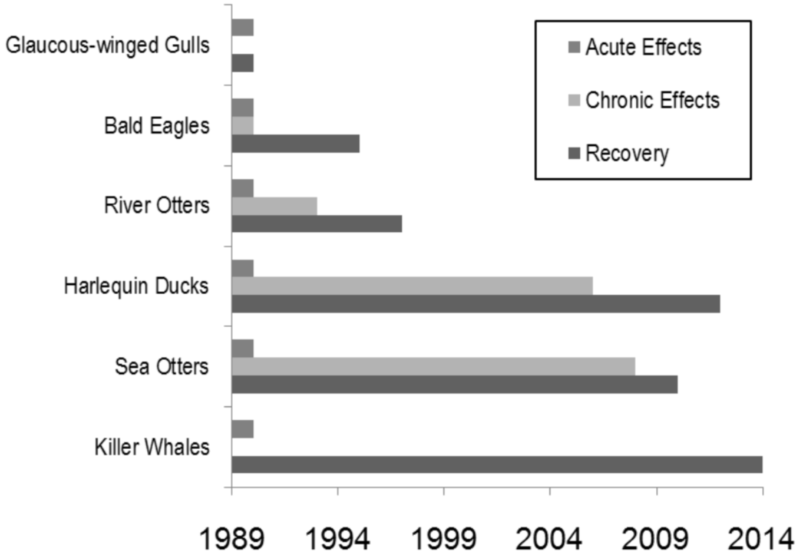


Exhibit 3. Figure 11 from the report by Michel et al. (2016). Recovery timelines for several key species affected by EVOS.

Decades of exposure to lingering oil and the chronic effects observed for sea otters and harlequin ducks has often made these species the focus of studies aiming to quantify the level of exposure in wildlife. These species were both declared recovered in 2014 according to EVOSTC criteria. Killer whales are the only species discussed that have not been classified as recovered; populations have yet to return to pre-spill numbers, but the lack of recovery is not attributed to chronic effects of lingering oil exposure.

The study also evaluated subsistence use and harvest of ecological resources. Post-EVOS subsistence use of PWS was investigated with household surveys performed in 2003 and 2014. The 2003 survey responses indicated lower subsistence use since the EVOS, with 83% of households stating their use of at least one subsistence resource was lower than before the spill, and 39% attributing the decline to reasons related to EVOS. Almost three quarters (72%) of respondents stated the traditional way of life has not recovered from the effects of the spill, and 78% reported injured subsistence resources have not recovered to pre-spill levels. The 2014 survey responses showed an increase in confidence in the safety of consuming subsistence foods, but those who did express safety concerns commonly cited EVOS as the reason.

3.1.8 Nixon and Michel (2018): A Review of Distribution and Quantity of Lingering Subsurface Oil from the Exxon Valdez Oil Spill

Nixon and Michel (2018) reviewed the causal geomorphic and physical mechanisms for persistence of oil in the intertidal subsurface sediments of PWS beaches impacted by the EVOS and updated previous models to characterize the present-day linear and areal spatial extent and quantity of lingering subsurface oil.

Authors provide a review of historical surveys of lingering oil, update datasets with additional surveys, and update previously developed modeling efforts to provide present-day estimates of linear and areal spatial extent and mass of lingering subsurface oil. To update models, authors compiled information related to distribution and quantity of lingering oil, along with geomorphic, physical, chemical, and microbial mechanisms correlated with subsurface oil persistence in PWS. Modeling methods primarily followed Nixon and Michel (2015) and other previous work by this research group.

In the updated dataset developed for this effort, subsurface oil was observed on 94 of 311 (30%) distinct beach segments from 2001–2015 and in 631 of a total of 14,405 (4%) test pits, with average oiled sediment layers ranging from 5 to 20 cm, buried beneath 10 to 20 cm of clean sediments. The updated dataset also indicated that 80% of remaining lingering subsurface oil is above mean sea level (msl), though thickness of oiled layers is greatest on average at or just below msl. The model performs well based on the probability of encountering oil and empirical results of lingering oil surveys; model predicted probabilities of encountering oil are shown below.

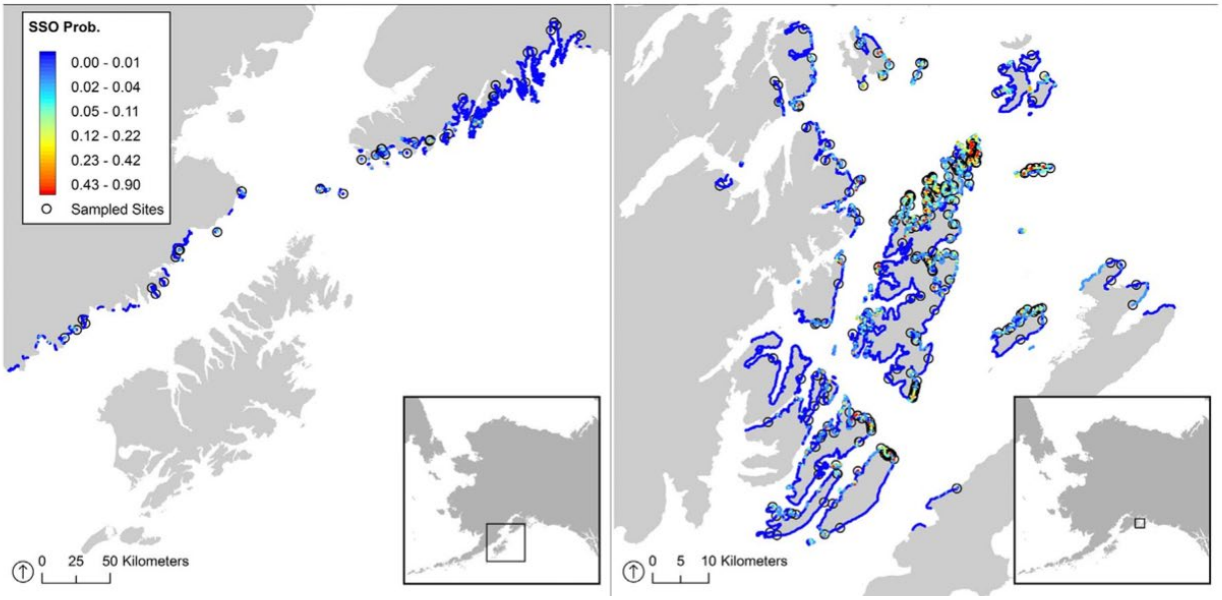


Exhibit 4. Figure 5 from the report by Nixon and Michel (2018). Model-predicted subsurface oil (SSO) encounter probability for 2,545 km of shoreline in modeled extent. All sites surveyed for subsurface Exxon Valdez oil in PWS and along the outer coast of the Gulf of Alaska shown as circles.

The quantity of lingering oil was also estimated using the updated dataset—227 tons of subsurface oil are estimated to remain across 27.6 ha of intertidal area along 10.4 km of shoreline in PWS. A much smaller mass of oil is estimated to be remaining in the Gulf of Alaska.

The study concluded that persistence of lingering oil is associated with finer grain sand and gravel sediments and is located in areas of heavy initial oiling that are sheltered from natural disturbance patterns (wave energy, groundwater flow). Additional factors identified in this study include presence of exposed bedrock out crops serving as breakwaters and presence of an armored or imbricated layer of coarse surface clasts over a finer layer of sediment at moderate wave intensity sites. At low energy sites, the steeper intertidal slope and presence of angular, boulder rubble were predominant factors.

Lastly, authors summarize previous studies regarding bioavailability of remaining oil, which is indicated to be low unless disturbed, and natural pathways for removal of remaining subsurface oil, which include physical disturbance by wave energy, physical disturbance by organisms, and microbial degradation. Storm driven high energy wave events are the current primary driver.

3.1.9 Short and Maselko (2023): A Quantitative Comparison of Oil Sources on Shorelines of Prince William Sound, Alaska, 17 Years After the Exxon Valdez Oil Spill

The goal of this study was to estimate the amount of Monterey Formation oil remaining on PWS shorelines from oil storage tank ruptures during the 1964 Alaska earthquake and to compare this to previous estimates of remaining EVOS oil and oil from human activity sites prior to and within the trajectory of EVOS.

Short and Maselko analyzed data collected from a 2006 survey of 98 beach segments within PWS and a 2007 survey sampling 102 segments. Segments were visually examined for the presence of oil, and Monterey Formation tar balls and tar mats were also identified by visual characteristics. When oil deposits were unable to be visually determined, the source of the oil was confirmed with the ratio of di- and trialkyl-substituted dibenzothiophenes to similar substituted phenanthrenes/anthracenes, which was done with a gas chromatography-mass selective detector. Oil was measured by approximating the mean thickness of oil with a ruler and surface area was calculated through digitization of photographs of oil patches.

When comparing the presence of Monterey Formation oil to EVOS, estimated Monterey Formation oil area (0.0086 ha) and mass (639 kg) were below estimates for EVOS oil area (11 ha) and mass (83,400 kg). EVOS tPAH estimates were also compared to human activity tPAH estimates, with EVOS tPAH mass (1230 kg) being more than double the mass of human activity tPAH estimates (567 kg). Overall, EVOS was determined to be the main source of long-term hydrocarbon contamination on PWS shorelines. However, the 1964 spill occurred 25 years prior to EVOS, so direct comparisons of oil remaining from each in 2006 might not be entirely appropriate.

3.2 Ecological Impacts

3.2.1 Arimitsu et al. (2018): Monitoring Long-Term Changes in Forage Fish Distribution, Abundance, and Body Condition

Arimitsu et al. (2018) summarized the results of forage fish survey in PWS during summers from 2012 to 2016. Determining the abundance of forage fish is challenging due to their complex life history, and this report established methods to effectively monitor them through a combination of arial and acoustic-trawl surveys.

The annual monitoring revealed that the abundance of young walleye pollock (*Gadus chalcogrammus*), capelin *(Mallotus villosus*), sand lance (*Ammodytes personatus*), and krill (*Euphausiacea*) was lowest in 2015. Observed reductions in abundance of these species coincided with anomalously warm ocean conditions that occurred in the region from 2014 to 2016. These warmer conditions are attributed to better outcomes for some species of herring (but not Pacific herring) and gelatinous zooplankton. Additionally, body condition was affected with reduced sizes of multiple species. For example, capelin weight at length was 20-30% lower in 2014 to 2015 compared to 2013; sand lace weight at length was 10-35% lower in 2013 to 2015 compared to 2012.

While this work does not directly measure the effects of oiling on fish, it does provide valuable information about prey species abundance and trends in PWS, which may influence dependent wildlife species that are still recovering from EVOS. Additionally, this report also provides useful evidence that climatic changes can influence the abundance of prey in PWS and the reduced forage fish abundance may further hamper the ability for injured predator species to recover.

3.2.2 Barron et al. (2020): Long-Term Ecological Impacts from Oil Spills: Comparison of Exxon Valdez, Hebei Spirit, and Deepwater Horizon

Barron et al. (2020) provides a review and summary of three oil spills differing in volume, oil composition, location, and response actions—EVOS, Deepwater Horizon (DWH), and the Hebei Spirit oil spill (HSOS)—with a focus on long-term ecological effects and recovery. As described by Barron et al. (2020), the ecological impacts of the EVOS include both acute and long-term ecological impacts. Acute effects included mortality of sea birds, sea otters, harbor seals, killer whales, salmon, and herring eggs. Acute impacts led to long-term injury in some cases—for example, the AT1 pod of killer whales experienced high mortality following the spill, suffered low recruitment in the years since, and is not expected to recover. The intertidal zone was impacted by oil and cleanup activities, resulting in loss of algal cover and reduced invertebrates for up to 8 years. Evidence of PAH exposure was observed until 2011 based on 7-ethoxyresorufin-O-deethylase activity (EROD) monitoring in harlequin ducks. Long-term rates of recovery have been highly variable among species—as of 2014, the AT1 killer whale pod, Pacific herring, marbled murrelets, and pigeon guillemots are not recovering, but many monitored species have recovered. In some cases, interpretation of the impacts of the EVOS is confounded by other ecological processes and effects. The Pacific herring are an example of this, where population collapse four years after the EVOS likely reflects a combination of factors: poor nutritional condition, disease, and effects of high EVOS-related mortality on density-dependent effects in future years.

The HSOS and DWH are compared to the EVOS in terms of release differences (heavy versus light oils, climate, response actions) and long-term impacts. A key difference with the HSOS was the extensive initial removal of HSOS oil from shorelines and open water using oil booms and absorbents, recovery of slick oil at the surface, and application of oil spill dispersants. The HSOS also occurred in an area of higher wind and tidal energy, adding to oil dispersion. Response actions are credited with faster ecosystem recovery compared to EVOS and DWH. Concentrations of TPH and PAH reached background levels in seawater, sediment, and oysters within 18 months, and EROD monitoring of fishes reached background levels within two to four years. Long-term monitoring has focused on macrobenthic communities due to the low pre-spill abundance of marine mammals and seabirds in the region. In contract, the DWH spill impacted a wider variety of ocean environments, including deep ocean communities and offshore aquatic, shoreline, and coastal habitats. Deep ocean impacts persisted for up to three years due to higher sedimentation and lack of bioturbation. Impacts to marine mammals, sea birds, and pelagic fish in the offshore aquatic habitat were documented. In the coastal environment, impacts from oiling and response actions affected aquatic vegetation in marshes, resulting in changes to vegetation population structure and long-term reduced survival of dolphins in Barataria Bay.

The authors conclude this review by noting that response actions, intensity of wave, wind, and tidal actions, and specifics of the ecological community exposed are key factors driving recovery rates and providing lessons learned.

3.2.3 Bodkin et al. (2018): Variation in Abundance of Pacific Blue Mussel (*Mytilus trossulus*) in the Northern Gulf of Alaska, 2006–2015

Bodkin et al. (2018) monitored seven metrics of blue mussel (*Mytilus trossulus*) abundance in three regions of the Gulf of Alaska to evaluate population health. Five sampling sites were selected in each region (Katmai National Park and Preserve, Kenai Fjords National Park, and western PWS) to evaluate spatial and temporal variation in metrics of blue mussel abundance. Metrics included the percent cover evaluated at two tidal heights, density of large mussels (> 20 cm), density of all mussels > 2 cm, mussel bed size, and total abundance of large and all mussels.

The survey methods followed standard operating procedures developed and peer-reviewed under the National Park Service Inventory and Monitoring Programs. In each study region, five sheltered rocky habitat sites were selected by identifying appropriate shoreline types and using generalized random tessellation stratified sampling. Sampling occurred yearly in June and July at Katmai Fjords from 2006–2010 and 2012–2015, at Kenai Fjords from 2008–2015, and at PWS in 2007 and from 2010–2015. Percent cover of mussels, sessile invertebrates, and algae were measured in fixed 50-meter transects at 0.5 meters and 1.5 meters above mean lower low water (MLLW). Additionally, nearby mussel beds were measured for size and density of large mussels, and all size and density mussels using core samples. Data were evaluated using a set of general linear models to evaluate how mussel abundance might vary over space and time.

The authors present results of 21 information-theoretic analyses using general linear models for large mussel density, mussel core density, contiguous bed size, large mussel abundance, and mussel core abundance. These models provide varying strengths for the influence of site and year sampled on the various abundance metrics to inform spatial and temporal patterns, and were then evaluated for best fit and predicative ability. Results indicated two key findings: conditions relative to small spatial scales are an important influence on mussel abundance, and broad temporal patterns are evident, with higher abundance in earlier and later sampling years across the Gulf of Alaska. Spatial factors influencing variation across smaller scales include degree of exposure, slope, and substrate. Additionally, environmental factors such as tidal elevation, salinity, temperature, and disturbance are known to influence mussel abundance on smaller spatial scales. Across all sites, a wider temporal pattern was identified for larger mussel abundance, showing relatively high abundance during initial sampling events, a subsequent decline of up to 85% in some locations, and a recovery of greater than 41% and up to near initial levels in some sites by 2015. The temporal trends were not evident in core samples of mussel density, which the authors consider an index of recruitment and indicative of a consistent recruitment of young mussels. The rate and magnitude of change observed for mussel abundance in this study suggests high rates of annual recruitment of juveniles into mussel beds and widespread temporal variability in post-recruitment mortality. While this study did not directly examine effects of lingering oil, it provides valuable information on factors influencing blue mussel populations trends in PWS and the Gulf of Alaska.

3.2.4 Campbell et al. (2023): Monitoring the Oceanographic Conditions of Prince William Sound

Campbell et al. (2023) monitored temporal and spatial changes in physical and biological oceanographic conditions within PWS, with the objectives of continuing the ongoing time series of physical, biogeochemical, and biological parameters in PWS. This was achieved by conducting vessel-based surveys, maintaining the time series capturing data on hydrography, plankton, and nutrients to support herring research, and installing equipment to acquire frequent readings on oceanographic conditions and in situ observations of zooplankton, large phytoplankton, and other particles. Measurements of conductivity and temperature at depth, water sampling for nutrient and chlorophyll analysis, and a zooplankton tow were carried out at each station. The monitoring data was combined with previous time series to compare trends over years.

Temperature in PWS shows an overall warming trend (0.1–0.2 degrees Celsius [°C]) per decade, aligning with long-term increases in heat transfer to the ocean's surface. Extreme temperature events such as the 2013–2015 heatwave and the 2019 heatwave has impacted plankton community composition and productivity. The lowest observations for net primary productivity have occurred after the 2013–2015 heatwave, and there has been a 38% decline in overall productivity throughout the course of the time series. Potential reasons for this decline include thinning of the mixed layer in PWS, which results in less total nitrate available to producers, thereby reducing productivity.

Looking at plankton community composition, warm water taxa became more common after the 2013–2015 heatwave, while subarctic species declined in prevalence. The shorter duration of the 2019 heatwave appeared to have less of an influence on zooplankton composition, and changes were shorter-lived. While this study did not look at the effects of lingering oil directly, oceanographic conditions play an important role in recovery of species from the EVOS, and this study provides recently updated trends for these variables.

3.2.5 Coletti et al. (2023): Nearshore Ecosystems in the Gulf of Alaska

Coletti et al. (2023) examined nearshore ecosystems in four regions within the EVOS-affected area, including PWS, Kenai Fjords National Park, Kachemak Bay, and Katmai National Park and Preserve. The objectives of this study were to determine the status of and evaluate patterns of change in nearshore species and communities, identify temporal and spatial extent of changes, identify potential causes of change in biological communities, identify factors affecting present and future trends in population and ecosystem status, and communicate results to the public/resource managers. Additionally, the effects of the Pacific marine heatwave and sea star wasting disease on nearshore marine ecosystems were evaluated. Data used for this study included Gulf Watch Alaska sampling from 2012–2016 and 2017–2021.

The Pacific marine heatwave increased temperatures within intertidal waters of the Gulf of Alaska beginning in 2014. While the full extent of the impacts this heatwave had on nearshore habitats are unclear, the Pacific marine heatwave was responsible for a shift in the community structure in rocky intertidal habitats; declines in macroalgal foundation species were noted, and there was a region-wide shift towards a filter-feeder dominated state. This widespread change in rocky intertidal community structures emphasizes how the influence of local conditions can be negated by large-scale events such as the Pacific marine heatwave. However, the effects of the heatwave on nearshore ecosystems were not as dramatic as seen in the pelagic food web, where large declines in forage fish abundance and quality were noted.

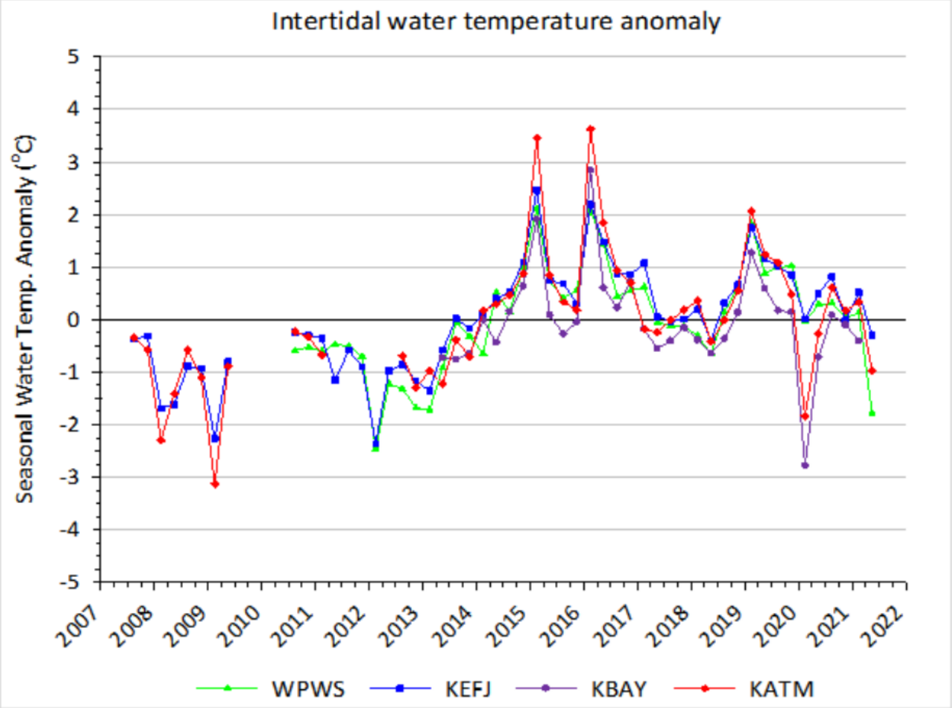


Exhibit 5. Figure 6 from the report by Coletti et al. (2023). Seasonal water temperature anomalies for PWS, Kenai Fjords National Park, Kachemak Bay, and Katmai National Park and Preserve.

An outbreak of sea star wasting disease occurred during the recent Pacific marine heatwave, leading to declines in sea star abundance within the northern Gulf of Alaska. It was proposed that the changes in community structure along with the outbreak in sea star wasting potentially had synergistic effects; sea stars are important predators of mussels, and a decrease in sea star predation combined with macroalgal declines giving more space for mussels may have allowed for increased mussel abundance. The increase in mussel abundance has implications for nearshore biodiversity as well as for populations of nearshore vertebrate who consume mussels.

Nearshore bird communities were investigated across both spatial (Kenai Fjords versus Katmai National Park) and temporal (between seasons) scales; community trends before and after the Pacific marine heatwave were investigated. Differences between regions were minimal, however seasonality was found to play a large role in the bird community composition; winter coastal birds showed an increase in benthic consumers, while summer marine bird communities were primarily composed of forage fish consumers. With regards to the Pacific marine heatwave, birds consuming forage fish or zooplankton showed differences in abundances, while birds consuming benthic invertebrates were stable in terms of abundance.

The Pacific marine heatwave did not impact sea otter abundance; however, there were noted shifts in sea otter diets. Increased mussel consumption by sea otters coincided with the increase in mussel abundance brought on by the Pacific marine heatwave and sea star wasting. Sea star wasting also resulted in a reduction in the abundance of sea stars consumed by sea otters, with sea stars representing less than 2% of sea otters diets in PWS and Katmai National Park, relative to previous maximums of 14% and 10%. The proportion of clams in sea otter diets were noted to decrease with decreased clam biomass and increased sea otter abundance in Katmai National Park as well. This study focuses on the significant effects the Pacific marine heatwave had on community structure, which may complicate species recovery in PWS; the study did not focus on specific effects from lingering oil.

3.2.6 Cushing et al. (2018): Patterns of Distribution, Abundance, and Change Over Time in a Subarctic Marine Bird Community

Cushing et al. (2018) evaluated trends in marine bird population across PWS using data collected during marine bird surveys conducted between 1989 and 2012 for the EVOS long-term monitoring program, with a focus on how habitat and climate variability influence population trends.

Marine bird surveys conducted under this project followed methods consistent with EVOS long-term monitoring. PWS was divided into three strata: shoreline (all waters within 200 meters of land), coastal-pelagic (nearshore), and pelagic (offshore). PWS was then sampled using a stratified random sampling approach with transects along the shoreline and 5-minute latitude blocks in the offshore areas. From the survey dataset, Cushing et al. (2018) excluded genera not surveyed in every year, or with an occurrence of less than 5% within one of the strata, resulting in a total of 18 genera evaluated. Each genus was categorized by EVOS impact (using impact determinations from the EVOSTC), and by feeding habits (as either pelagic, benthic or mixed benthic pelagic feeders). Habitat factors considered included water depth, distance to shore, mean sea surface salinity, mean sea surface temperature, shoreline wave exposure, and shoreline substrate composition. Spatial and temporal patterns of marine bird community composition were statistically evaluated using ordination—a family of statistical methods used to extract common signals from correlated multivariate data; specifically, nonmetric multidimensional scaling was applied in this study.

Spatially, most (86.9%) of the variability in marine bird community composition among transects was accounted for by “onshore-offshore” and “marine-estuarine” environmental gradients (i.e., distance to the shore and depth). Much of the remaining variability was explained by salinity gradients and shoreline exposure.

Temporally, 3 of the 18 evaluated genera showed significant increases in abundance between 1989–2012, including cormorants, great blue herons, and harlequin ducks. In contrast, 8 of the 18 evaluated genera showed significant decreases in abundances over the same period, including storm-petrels, scoters, Bonaparte's gull, arctic tern, jaegers, pigeon guillemot, murrelets, and puffins. Greater proportional declines were observed for pelagic feeders (compared to benthic or benthic and pelagic), for species designated as not injured by the EVOS (compared to injured species), and for offshore species (compared to onshore). This study did not look at the effects of lingering oil on marine birds directly, but identifies and provides overarching trends for factors influencing marine bird populations in PWS.

3.2.7 Esler et al. (2018): Timelines and Mechanisms of Wildlife Population Recovery Following the Exxon Valdez Oil Spill

Esler et al. (2018) reviewed and summarized the timelines and mechanisms of wildlife recovery in PWS area following the EVOS. This paper uses the EVOSTC definition of recovery. The criteria of recovery varies from species to species, but generally requires a return to theoretical conditions that would exist had the oil spill not occurred, and abatement of exposure of animals to hydrocarbons lingering since the spill. Below is a summary table of the species reviewed and whether they are considered recovered or not recovered as of 2018.

Exhibit 6. Figure 1 from the report by Elser et al. (2018), modified to capture discussions results and tabulated herein.

Common Name (Species)	Status (year recovered) or possible reasons for lack of recovery
Glaucous-winged gulls (*Larus glaucescens*)	Recovered (1990)
Bald eagles (*Haliaeetus leucocephalus*)	Recovered (1995)
River otters (*Lontra canadensis*)	Recovered (1997)
Pigeon guillemots (*Cepphus columba*)	Not recovered; chronically exposed to lingering oil until 2004, predation from American mink, decrease in growth correlating to changes in climate/ecology, changes to pelagic food web (possibly independent of EVOS)
Marbled murrelets (*Brachyramphus marmoratus*)	Not recovered; decrease in growth correlating to changes in climate/ecology, changes to pelagic food web (possibly independent of EVOS)
Sea otters (*Enhyrda lutris*)	Recovered (2014)
Harlequin ducks (*Histrionicus histrionicus*)	Recovered (2014)
Killer whales (*Orcinus orca*)	Not recovered; recovery constrained by demographic factors associated with life history characteristics and small population size

As of 2018, many species are considered fully recovered, including glaucous-winged gulls, bald eagles, river and sea otters, and harlequin ducks, while other species including pigeon guillemots, marbled murrelets, and killer whales have not. The mechanisms leading to both the injury and recovery timelines of populations vary greatly between the different species. Some species have recovered quickly following the acute exposure, some species took decades, and some have yet to recover. While this review doesn't evaluate the effects of lingering oil on recovery specifically, it highlights that the recovery of certain species can be further hampered by natural and anthropogenic influences that make it challenging to determine exactly what is responsible for the continued decline of the population.

3.2.8 Gorman et al. (2018): Spatial and Temporal Variation in Winter Condition of Juvenile Pacific Herring (*Clupea pallasii*) in Prince William Sound, Alaska: Oceanographic Exchange with the Gulf of Alaska

Gorman et al. (2018) measured the spatial variability in measures of whole-body energy density of juvenile Pacific herring in PWS over 9 years, with the objective of understanding the environmental factors shaping nutritional processes and quality (growth/health) of these juvenile herring. To accomplish this, the study sampled juvenile herring from a total of 19 nursery bays in

PWS in March and November from 2007 to 2016. These herring were then analyzed by bomb calorimetry to determine how energy dense their tissue was. One key finding of this study was that temperatures are associated with the quality of the herring, with cold environmental conditions enhancing the energy density of the fish, while warm environmental conditions reduced juvenile herring quality. The fish were the most energy dense in 2012–2013 and least energy dense in 2015, which coincides with the Pacific marine heatwave.

The study also established that zooplankton community structure and abundance act as important transport mechanisms for energy from the Gulf of Alaska to PWS juvenile herring. While this study did not measure the effects of lingering oil on Pacific herring, it does help clarify factors that influence the ability of the population to recover from EVOS, and suggests that climate change may affect the growth and development of Pacific herring in PWS.

3.2.9 Hershberger et al. (2023): Herring Disease Program II

Hershberger et al. (2023) summarized the pathogen and disease studies performed from 2017 to 2022 under the Herring Research and Monitoring Program. It updates annual field surveillances for *Ichthyophonus* and viral hemorrhagic septicemia virus (VHSV) infection prevalence in adult and juvenile Pacific herring in PWS and reference locations, including Sitka Sound, Alaska, and Puget Sound, Washington.

Ichthyophonus infections remained endemic in Pacific herring throughout the Northeast Pacific region, with infection prevalence in PWS ranging from approximately 10–20% from 2017 to 2022. It is unclear how the *Ichthyophonus* parasites are being transmitted to the herring; studies have shown that the parasite is not transferred through cohabitation or through plankton acting as an intermediate host. One hypothesis is that the parasite is transmitted through the consumption of infected fish eggs. Additionally, herring susceptibility to *Ichthyophonus* increases following embryonic exposure to PAHs.

VHSV was not isolated from Pacific herring during the study period; however, neutralizing antibodies have been detected in the fish sampled during this period, indicating the fish may still be exposed to VHSV. Levels of VHSV antibodies decreased from being detected in approximately 10% of animals (2017–2018) to approximately 1% (2019–2022). Temperature was shown to play a role in VHSV shedding, with increased shedding occurring at cooler temperatures. Homologous and heterologous DNA vaccines are effective at immunizing Pacific herring against VHSV. Controlled laboratory studies determined that herring early life stage exposure to oil does not impact their susceptibility to VHSV, and under some conditions, had decreased susceptibility to VHSV.

This report adds valuable information about pathogen monitoring for Pacific herring in the Alaska region, including PWS. It provides information on mechanisms of *Ichthyophonus* and VHSV transmission, tools for measuring prevalence, and immunization techniques for Pacific herring. The role lingering oil may play in the susceptibility of Pacific herring is dependent on the pathogen: exposure of herring embryos to oil increases their susceptibility to *Ichthyophonus*; exposure of early life stages of herring to oil sometimes decreases their susceptibility to VHSV.

3.2.10 Kaler et al. (2018): Prince William Sound Marine Bird Surveys

Kaler et al. (2018) presented the final report of an EVOSTC project monitoring marine birds in PWS following the EVOS. United States Fish and Wildlife Service began conducting marine bird surveys prior to the EVOS in 1972, allowing for a comprehensive pre- and post-EVOS data set spanning 1972 to 2016. Data for 2012, 2014, and 2016 were collected as part of this project, and post-spill surveys are evaluated to assess recovery.

Marine bird surveys conducted under this project followed methods previously employed for marine bird surveys as part of EVOS long-term monitoring. Briefly, PWS was divided into three strata: shoreline (all waters within 200 meters of land), coastal-pelagic (nearshore), and pelagic (offshore); and sampled using a stratified random sampling approach with transects along the shoreline and 5-min latitude blocks in the offshore areas. Surveys were conducted using the same methodology and same transects for all surveyed years from 1989 to 2016. All surveys were completed in summer. To evaluate trends with respect to lingering EVOS oil, PWS was post-stratified into oiled and unoiled areas. Post-stratification analyses assumed that bird populations in the oiled and unoiled portions of PWS, as well as PWS as a whole, were discrete, as data on bird movement was limited. Populations for each area were estimated from surveys and combining all PWS strata. Populations trends were evaluated for statistical trends over time using an alpha of 0.1 to balance Type I and Type II errors. Twenty taxa were evaluated, including those identified as injured following the EVOS (Barrow's goldeneyes, common loons, cormorants, harlequin ducks, bald eagles, black oystercatchers, common murres, pigeon guillemots, marbled murrelets, Kittlitz's murrelets, and sea otters) and additional taxa of interest (black-legged kittiwakes, buffleheads, grebes, glaucous-winged gulls, mergansers, mew gulls, Northwestern crows, scoters, and terns).

In oiled areas of PWS, increasing summer population trends were observed for three taxa (bald eagles, cormorants, and harlequin ducks), while decreasing summer population trends were observed for five taxa (grebes, mergansers, murrelets, pigeon guillemots, and terns). The remaining taxa did not indicate a statistically significant increase or decrease. Trends were also evaluated across all areas of PWS (oiled and unoiled), with increasing abundance of black oystercatchers and glaucous-winged gulls, and decreased abundance for grebes, murrelets, and pigeon guillemots. In addition to potential toxicity of lingering oil, factors that may contribute to slower recovery or a lack of recovery for some taxa include changes in abundance of prey resources such as schooling forage fish (including herring), increases in predation, increases in ocean temperature (surveys occurred during the Pacific marine heatwave), and other sources of environmental change and anthropogenic disturbance.

3.2.11 Konar et al. (2018): Long-term Monitoring: Nearshore Benthic Ecosystems in Kachemak Bay

Konar et al. (2018) summarized key trends and observations for nearshore benthic habitats in Kachemak Bay from 2012 to 2016, including rocky intertidal areas, seagrass beds, and soft-sediment beaches, with a focus on key taxa with high ecological value and an aim to differentiate between anthropogenic and natural stressors influencing observed trends. Specific goals included establishing trends in abundance and distribution of rocky intertidal plants, invertebrate, and seagrass beds, trends in abundance and size frequency of clams and mussels, as well as trends in sea otter abundance, diet, and mortality. Additionally, different environmental variables were measured to understand their relationship with observed trends. These variables included temperature as well as static environmental drivers (i.e., do not change over short time scales) such as measurements of substrate, exposure, fetch, and distance to freshwater and/or glaciers.

Looking at rocky intertidal communities, short-term dynamic drivers acting on a bay-wide scale were found to play a large role in variability; community shifts in similar directions occurred among sites, and common trends were observed over time. In addition, temperatures in the low intertidal zone were found to increase over the duration of the monitoring program. The increase in the spread of sea star wasting disease has been attributed to increased temperatures as a result of the Pacific marine heatwave, which was neither confirmed nor rejected. One quarter (25%) of the sea stars observed in 2015 were affected by the disease, specifically within the species *Evasterias troschelii*. However, conclusions regarding the long-term impact of this disease on sea star abundance are unclear, as there was a notable increase in abundance of *Evasterias troschelii* since 2015. Continued monitoring of this disease will be necessary for the protection of these critical species.

Size-frequency distribution of mussels appeared to differ between sites, which was attributed to oceanographic conditions at specific sites driving larval dispersal patterns, as well as the potential for local upwellings enhancing settlement by influencing larval retention. Clam variability also differed among sites, with abundance and composition being influenced by substrate, environmental conditions such as salinity, food availability, predation, and physical disturbances (e.g., storms). The lowest abundance of clams was observed within Port Graham, with the potential cause being a sandier substrate.

Trends within seagrass beds were inconsistent, indicating that factors influencing these trends are likely acting on a local rather than a regional scale. Sedimentation and competition were proposed as potential reasons for observed declines at different sites. The dramatic changes that occurred over the study period suggest long-term monitoring is necessary to determine whether recovery has stabilized.

Sea otters faced an “unusual mortality event” in 2006 in Kachemak Bay, leading to populations being monitored, particularly for Strep Syndrome. Strep Syndrome was still impacting sea otters in 2015; however, there are concerns that another viral infection could also be contributing to the observed mortalities, as the deceased otters with Strep Syndrome appear healthier than in the past. Harmful algal blooms were documented in Kachemak Bay from 2015 to 2016, and the influence on biotoxins (specifically in filter feeders such as mussels and clams) and how these biotoxins impact sea otters with Strep Syndrome remains to be investigated. Overall, this study provides a detailed look at population trends for multiple communities in Kachemak Bay.

3.2.12 McCammon et al. (2018): Long-term Monitoring of Marine Conditions and Injured Resources and Services

The Gulf Watch Alaska (GWA) program includes 15 scientific monitoring projects assessing environmental drivers (i.e., physical and biological oceanographic conditions), the pelagic ecosystem (i.e., recovery of forage fish, seabirds, humpback whales, and killer whales), the nearshore ecosystem (i.e., recovery of subtidal and intertidal habitats and species that were affected by the EVOS), and lingering oil in the Gulf of Alaska. Specific projects include long-term monitoring of pelagic fish, monitoring health and abundance of marine birds and mammals, monitoring and evaluating the impacts of biological processes such as whale predation on herring, and monitoring the presence, distribution, and weathering of lingering oil. Many of the long-term monitoring projects incorporated into GWA were previously funded by EVOSTC, representing a history of more than 40 years. Methods varied by program and are documented in individual project reports. Along with details on the overall program goals and achievements, the 2018 final report presents the first five years of scientific findings (2012–2016), with additional funding in place for five more years of monitoring (2017–2021).

GWA found that lingering EVOS oil remains in PWS at levels consistent with those observed in 2001. Lingering oil is primarily sequestered in subsurface sediments and therefore not biologically available to marine organisms, which is supported by data collected from passive samplers. Additionally, oil exposure metrics for nearshore foraging sea otters and harlequin ducks show little evidence for continued exposure in the oil-affected areas of PWS. At the population level, long-term marine bird surveys in PWS indicate that recovery is underway for many species, including bald eagles, cormorants, and harlequin ducks. However, populations of mergansers, murrelets, pigeon guillemots, and terns continue to decline. The AT1 pod of killer whales continues to decline post-EVOS, with no new calves since 1984.

Unrelated to lingering oil, GWA field sampling also captured a multi-year warm water anomaly, enhanced by El Niño conditions to create a multi-year Pacific marine heatwave (observed from 2013 to 2018). This warm water anomaly affected weather patterns and ecosystems across Alaska, and environmental or species changes during the anomaly were detected by all GWA programs. Effects to environmental drivers included increased temperatures throughout the water column, fresher (less saline) water at depth, a higher abundance of warm water copepod species and lower abundance of *euphausiids* such as krill, which are an important food for many species, including whales. Nearshore and pelagic monitoring programs documented the emergence of sea star wasting disease, increased paralytic shellfish poisoning, anomalous mortality events of seabirds and sea otters, and widespread reproductive failures of breeding seabirds. These climactic events may limit or delay recovery related to the EVOS.

3.2.13 Moran et al. (2023): Long-term Monitoring of Humpback Whale Predation on Pacific Herring in Prince William Sound

Moran et al. (2023) investigated the relationship between humpback whale and Pacific herring populations, with specific interest in the reasons for a lack of recovery in humpback whale populations following the 2014 to 2016 Pacific marine heatwave. The objectives for this study were to estimate trends in humpback whale abundance, diet, and distribution, evaluate prey quality and trophic position through analysis using bomb calorimetry and stable isotopes, and estimate the impact of humpback whale predation on herring. This study focuses on data from 2017 to 2021; however, data from 2007 to 2009 and 2011 to 2015 from previous projects were integrated into the analysis.

Prior to the Pacific marine heatwave, there was a documented increase in humpback whale numbers in PWS. However, as previously stated, the number of humpback whales in PWS has declined dramatically since the Pacific marine heatwave, with encounter rates dropping from an average of 0.22 ± 0.13 (mean ± standard deviation) whales seen per nautical mile traveled to 0.03 ± 0.02 in the years following the heatwave. Pacific herring are the primary source of food for humpbacks in PWS, which also faced declines following the increases in temperature brought on by the Pacific marine heatwave. Large shoals of herring would inhabit deeper waters prior to spawning, and whales were known to forage on these groups of herring. After the heatwave, there was a decrease in the quality of herring available to the whales, and whales were chasing smaller schools of juvenile herring. This behavior came at a higher foraging cost when compared to the larger shoals of herring in deeper waters, as the whales had longer search times, and the juvenile herring were less energy-dense than adult herring. These feeding behavior observations were supported by isotopic analysis, which revealed the whales in PWS are feeding at higher trophic levels than other humpbacks in the Gulf of Alaska.

While abundance of both herring and humpbacks declined initially after the Pacific marine heatwave, evidence suggests the herring have recovered to the pre-marine heat wave levels while whales have not. A potential explanation for the lack of recovery within humpback whale populations is a portion of the population not surviving the prey shortage following the decline of herring associated with the Pacific marine heatwave. The decline in whale populations could be potentially benefitting herring, however, as they are facing less predation pressure and increasing in abundance (although their overall population is still declined compared to pre-EVOS levels). This study provides valuable information on the roles prey abundance and climatic events play in species recovery in PWS.

3.2.14 Whitehead et al. (2023): Genomic Mechanisms that Underlie Lack of Recovery of Prince William Sound Herring Following the 1990s Collapse

Whitehead et al. (2023) seeks to determine what caused the collapse and subsequent lack of recovery of PWS Pacific herring, with three specific aims: 1) characterize the patterns of genetic change in PWS fish and reference populations through time to generate hypotheses about the causes and consequences of the Pacific herring crash following the EVOS; 2) test if early-life exposure to oil compromises the ability of later life stages to mount an effective immune response to common pathogens endemic to PWS herring; and 3) determine if PWS population varies from others in their ability to tolerate oil exposure during early life and/or to mount a robust protective immune response to viral pathogen.

Aim 1 was accomplished through sampling of Pacific herring tissue (from approximately 60 individuals per sample) across time from the Bearing Sea and PWS (1991, 1996, 2006, 2017), the Gulf of Alaska (1996, 2006, 2017), as well as outside of Alaska (British Columbia, Washington, California) in 2017. The whole genome of these populations was sequenced following a standard published procedure. The analysis revealed that the Bering Sea population is the most distinct among all populations of Pacific herring measured, which suggests that the Bering Sea environment may require adaptations that are distinct from the other parts of the species' range. Using mathematic modeling, the study measured changes in polygenetic selection over time in PWS population but not the other two Alaskan populations. This suggests that the environmental changes inPWS habitat in the decades following EVOS, the VHSV epidemic, and population collapse cumulatively exerted genotype-specific fitness changes on PWS fish.

Comparing the early time periods (1991–1996 versus 1996–2006), there was a significant enrichment in the early 1990s of genes involved in C-C chemokine receptor activity over time, which are important receptors for immune system signaling. This is consistent with PWS population evolving in response to the VHSV epidemic, but additional confirmation is required.

Overall, these findings promote the hypothesis that the VHSV viral epidemic that affected PWS population in the early 1990s was a selective force leading to evolutionary changes in the innate immune system of PWS fish. Though contemporary PWS fish do not vary in their sensitivity to acute mortality induced by laboratory exposure to VHSV, responses that are more subtle than acute lethality may be relevant and important, such that this hypothesis merits further study.

Study aims 2 and 3 were evaluated through controlled laboratory studies by collecting eggs and sperm from herring in the spring of 2018. Eggs were fertilized in a laboratory prior to testing. The embryos were exposed to weathered Alaskan North Slope crude oil (weathering achieved by heating to 60°C in a water bath until the volume decreased by 10%), using a flow through exposure with filtered sea water. The embryos were exposed to six concentrations of PAHs ranging from 0.01 (no oil) to 3.5 micrograms per liter (µg/L), which cover the range of concentrations of PAHs that the Pacific herring were exposed to in PWS during the EVOS. Concentrations of PAHs were verified in the dosing water and animal tissues.

The transcriptomic responses to oil exposure in the early life stage animals across a broad range of doses and time are still being analyzed (due to the size and depth of the dataset). However, the study did reveal that changes to transcription following embryonic exposure to oil occur even at the lowest concentrations of exposure, and as quickly as within one day of exposure. The genes affected early are mostly Phase I and II metabolism genes, which, along with the body burden data that peaks at 4 days post fertilization and decreases by 10 days post fertilization, suggests that the embryos are able to respond metabolically to PAHs. Exposures to higher doses caused developmental deformities, particularly in the heart. Exposure during embryo development did not affect later-life sensitivity to virus exposure, but oil exposures after hatching (during mid-larval development) did. These results suggest there is a specific temporal window of sensitivity for Pacific herring to oil exposure during larval development that can lead to persistent effects into adulthood.

Comparisons in the physiological responses to the oil and VHSV between populations (PWS, Sitka Sound, and Washington) do not indicate that PWS fish are distinct in their response. There were differences in molecular responses between the Alaskan (PWS/Sitka Sound) and Washington fish for genes associated with the cardiovascular pathway, and these changes in expression may explain the reduced sensitivity to cardiovascular injury observed in the Washington population in response to oil exposure compared to Alaskan. However, the cause of these changes is difficult to discern without results from additional populations to compare.

Overall, this report by Whitehead et al. (2023) includes a deep and rich set of population genetics data. The data indicates that PWS population experienced changes to their genome in the three decades following the EVOS, VHSV epidemic, and collapse. Preliminary results have revealed certain genes involved with the innate immune response have been affected, but the analysis is ongoing. Oil exposure during embryogenesis did not affect later-life sensitivity to oil, but larval exposures did. Since the immune system develops after hatching, additional experiments could elucidate the exact time period during larval development in which herring are sensitive to oil exposure. The data within this project is still being actively interpreted and additional discoveries may be made.

3.3 Socioeconomic and Traditional Ecological Knowledge Effects

3.3.1 Fall et al. (2016): Update on the Status of Subsistence Uses in Exxon Valdez Oil Spill Area Communities, 2014

Fall et al. (2016) analyzed data collected in 2014 on subsistence use and harvest in the EVOS affected communities of Cordova, Tatitlek, and Chenega Bay. Additionally, information on Nanwalek and Port Graham (lower Cook Inlet EVOS affect communities) was obtained from another study. The goals of this study were to evaluate whether populations of subsistence fish and wildlife were at pre-spill levels and whether these resources were regarded as safe to eat, as well as to assess if cultural values associated with subsistence use had been reintegrated into EVOS communities. Using a census survey of households along with interviews from study communities, subsistence use in 2014 was estimated, harvest use was compared to previous years, harvest areas and changes within harvest areas were mapped, demographic and employment data was provided, the availability of resources and consumption safety were evaluated, and qualitative information on subsistence use was provided.

Harvest estimates (pounds per capita) and diversity were considerably lower in 2014 than the 2003 post-spill and pre-spill estimates. Survey participants gave several reasons for declines in subsistence harvest and use. While natural resource conditions were cited to play a role in the decline, personal reasons and lower levels of effort were often given as reasons leading to lower harvesting. Other socioeconomic factors mentioned include rising costs of equipment and fuel, younger generations being disinterested in subsistence use, and the traditional way of life having not yet recovered from the effects of EVOS.

Natural resource conditions were also brought up as reasons for lower subsistence use, with respondents referencing declines in availability of certain resources due to commercial overharvests, pressures from sport fishing charter operations, water pollution, and warming water temperatures. Respondents also stated that some resources had not recovered from lingering EVOS effects and voiced their awareness of residual oil within areas of harvest. Food safety was not commonly cited as a concern, however participants who did voice concerns frequently cited EVOS contamination as the source, especially with regards to Pacific herring and clams.

Overall, many respondents attributed the decline in subsistence harvest and diversity to the knowledge regarding subsistence use not being transferred to younger generations, declines in or difficulty accessing natural resource populations, and the traditional way of life not recovering from EVOS. Recommendations for increasing subsistence use in the future include supporting youth and elder engagement to promote the transfer of subsistence knowledge, involving subsistence users in natural resource management, providing more opportunities in the subsistence sectors of local economies, establishing programs for fishing, hunting, and gathering activities, and supporting long-term monitoring of natural resource populations. Fall et al. also noted the difficulty of separating EVOS effects from broader changes in socioeconomic conditions, and emphasizes that a return to pre-spill conditions is not possible, which needs to be considered when developing future plans for the recovery of EVOS affected communities.

3.3.2 Keating et al. (2020): Recovery of a Subsistence Way of Life: Assessments of Resource Harvests in Cordova, Chenega, Tatilek, Port Graham, and Nanwalek, Alaska Since the Exxon Valdez Oil Spill

Keating et al. (2020) investigated subsistence use in EVOS-impacted communities by utilizing household records, person records, income records, and harvest detail records alongside qualitative survey responses and interviews to understand economic, social, and cultural factors that have influenced subsistence harvest. Additional objectives include understanding characteristics of productive households (in terms of subsistence food production), the role commercial fishing has played in subsistence production, and perceived changes in resource abundance and quality related to EVOS.

Methods for analysis included an initial literature review for relevant background information pertaining to concentrations of wild foods production and patterns of distribution as well as characteristics of productive households. The literature review was followed by a quantitative analysis of household-level data, where households were classified by type, characteristics of productive households were identified, and patterns of subsistence resource productivity and distribution were established amongst household types.

Notably, the study identified decreased per capita harvest levels in 2014 in comparison to previous years, including pre-spill estimates. Other trends in subsistence use include an increase in household specialization for certain resources (e.g., salmon), higher resource diversity in elder households, and higher subsistence use and harvest in commercial fishing households, all of which are trends observed throughout Alaskan subsistence communities. The primary causes for declines in harvest and use were attributed to traditional knowledge not being passed down through generations, in addition to the introduction of digital technology. Additional causes for decline include increases in charter boats and sport hunters, as well as an increased demand for local, easily accessible resources such as marine invertebrates. When looking at the impacts of EVOS on subsistence use, community members cited changes in the economy from oil spill payments leading to an increase in consumption of commercial foods. This dependence on commercial foods led to less maintenance of equipment necessary for harvest of subsistence resources, which then led to a higher demand for local, easily accessible resources (resources that do not require extensive equipment) and higher harvest rates of local resources resulting in faster depletion rates. The increase in subsistence use and harvest in commercial fishing houses further emphasizes the importance of having access to well-maintained equipment. While the economic impacts of EVOS were cited as a potential reason for decline in subsistence use, lingering environmental issues from the spill had limited influence according to community members.

Overall, this study provided a qualitative and quantitative insight into socioeconomic trends in communities affected by EVOS and demonstrated the complexity of addressing the role EVOS plays in shifting economic and cultural practices and beliefs. Potential solutions proposed by community members for addressing culture changes that negatively affect subsistence use include improving youth education on traditional knowledge and necessary skills needed for subsistence harvest, particularly by bringing in elder community members who can contribute their expertise and pass along generational knowledge. When considering how subsistence communities can respond to future environmental disasters, providing temporary harvest grounds in other locations was proposed to facilitate subsistence use.

4. CONCLUSIONS

In the 34 years since the *Exxon Valdez* ran aground in PWS, there have been hundreds of studies conducted, making it one of the most studied oil spills. The goals and design of studies funded by EVOSTC have also evolved over the last 30 years, and the focus since 2015 has been understanding if and where lingering oil still occurs, if this oil is still bioavailable, and the role that changes to the ecosystem have on the ability of species injured by the oil spill to recover.

This review initially screened 53 reports/peer reviewed journal articles, of which 25 were summarized with annotated bibliographies. Of the initial 53 studies, 16 contained map figures, and three of those 16 contained access to digital geospatial data. For the studies that describe lingering oil and beaches, most of the studies reference the Boufadel et al. (2015) paper and the geospatial data within. Those data were compiled in a geodatabase provided with this review, along with minimal more recent data.

With efforts of georeferencing and more time spent tracking down digital data, the dataset could become more comprehensive. Some additional studies with data not accessible but worth pursuing are Short et al. (2023) and Nixon et al. (2018). Short et al. (2023) includes field observations in regions where we have no data (e.g., Stoney Island). While this study was published in 2023, it appears that the field observation data they use is from 2006. Nixon et al. (2018) includes modelled locations not captured in the modelled dataset in the geodatabase submittal. The additional modelled locations would hopefully include subsurface oiling that is less than MOR. Additionally, while there is no mention of it by Nixon et al. (2018), modelled surface oiling categories and locations would strengthen the GIS dataset (if available). There are also opportunities to include more photos in the geodatabase. Notably, there are downloadable photos from the Heintz et al. (2023) study that capture the conditions of the oiled beaches that they revisited in 2015 and 2021 (link to this data is in Table 2).

Recent surveys and mathematical modeling (Aderhold et al. 2018; Nixon and Michel, 2018) suggest that about 0.6% of oil from EVOS remains sequestered below 10 to 20 cm of clean sediment in intertidal areas and shorelines. Sequestered oil is not bioavailable unless disturbed, and due to the lack of bioavailability, the oil is unlikely to be degraded. Due to this lack of degradation/bioavailability, oiled beaches have not changed very much in terms of their oil classification, with those identified as “oiled” generally not changing in status since 2001. For example, there was no change in the classification of the nine sites revisited in the Heintz et al. (2023) paper which suggests there has been little degradation over the last decade.

Since EVOS, some species are considered to have recovered, some quickly within years, and others taking decades, those including glaucous-winged gulls, bald eagles, river otters, sea otters, and harlequin ducks. Yet, despite the spill occurring over 30 years ago, there are species that still have not recovered, such as pigeon guillemots, marbled murrelets, and killer whales. Changes to the environment that are unrelated to the EVOS has made understanding species recovery quite complex. Environmental drivers like marine heat waves, the climate pattern El Niño, as well as predator-prey interactions have been shown to exert some level of influence on the ability of species to recover.

The recovery of Pacific herring has been a focus of research, and the exact cause of the lack of recovery for this species is still not agreed upon. There are many different theories on the cause of their continued decline, and part of the complexity is likely a result of their status of being a forage fish in the middle of the food web, potentially affected by bottom-up pressures from changing ocean conditions affecting the availability of their prey, and the top-down pressure from recovering predator populations feeding on them. To further complicate matters, other factors such as salmon hatcheries and disease might affect recovery.

Declines in subsistence use and harvest have been noted in spill affected communities. Separating the influence of broader, unrelated changes in socioeconomic conditions from the role EVOS has played in the observed declines is challenging. However, surveys of community members revealed a commonly shared sentiment that the traditional way of life has not recovered from EVOS. Additionally, oil spill payments led to changes in local economies, resulting in an increase in the consumption of commercially sourced food.

Overall, the research conducted by EVOSTC funded projects is an invaluable contribution to the field of science, and their impact extends far beyond the Alaskan coastline. Understanding how variance in oceanographic conditions affects a wide range of species is valuable to scientists across the globe. The development of different techniques to monitor oil, and track population sizes are also widely applicable. The updated geospatial data provides valuable information on the over 250 field observations and the summary table provides additional studies that could be incorporated. Based on the studies reviewed, lingering oil is likely to persist for decades to come, and this long-term persistence should be considered with future monitoring efforts.

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TABLES

ATTACHMENTS