

TIMELINES AND MECHANISMS OF WILDLIFE POPULATION RECOVERY FOLLOWING THE *EXXON VALDEZ* OIL SPILL

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Background and objectives

In March 1989, the *T/V Exxon Valdez* ran aground in Prince William Sound (PWS), Alaska and spilled an estimated 42 million liters of crude oil (Wolfe et al. 1994). This oil subsequently spread over more than 26,000 km² of water surface in PWS and the Gulf of Alaska and landed on more than 1000 km of shoreline (Spies et al. 1996, Short et al. 2004; see Fig. 1 in Esler et al., this report). Initial consequences for wildlife were immediate and obvious. Mortalities due to oil in the weeks following the spill were estimated to be in the hundreds of thousands of marine birds (Piatt et al. 1990), several thousand sea otters (Garrott et al. 1993, Ballachey et al. 1994), significant proportions of resident (33%) and transient (41%) pods of killer whales (Matkin et al. 2008), and varying numbers of a wide assortment of other wildlife species. These levels of mortality are consistent with expectations, given the amount of oil spilled, the size of the oil-affected area, the abundance of wildlife in the area, and the known toxic and thermoregulatory consequences of exposure to oil, particularly in cold-water environments.

Other effects of oil spills on wildlife, including chronic or indirect effects, were not fully understood, recognized, or anticipated at the time of the *Exxon Valdez* oil spill (EVOS) (Peterson et al. 2003, Rice 2009). Thanks in large part to settlement funds managed by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC), including that for Gulf Watch Alaska in recent years, a considerable body of research has addressed wildlife recovery from the spill. This has allowed for an unprecedented and thorough understanding of the timelines and mechanisms of population recovery following catastrophic spills. In this document, we review the timelines and processes of recovery of wildlife from the EVOS. We also consider factors that result in variation in recovery times across species, and present recent data for two species that showed protracted recovery related to exposure to lingering oil, the sea otter (*Enhydra lutris*) and harlequin duck (*Histrionicus histrionicus*).

What is “recovery”?

The body of literature addressing wildlife recovery following the EVOS includes some controversy about occurrence, degree, and source of effects on individuals and populations (e.g., Irons et al. 2000, Wiens et al. 2001). Some of that controversy stems from varying definitions of recovery. Therefore, for the purposes of this document, we note explicitly that we are subscribing to the EVOSTC definitions of recovery (<http://www.evostc.state.ak.us/>). These definitions vary by species but generally require return to conditions that would have been present had the spill not occurred (acknowledging the difficulties associated with determining that) and also abatement of exposure of animals to hydrocarbons lingering since the spill (see Esler et al., this report).

Varying mechanisms of effect

The thorough considerations of injury and recovery of marine ecosystems following the EVOS have contributed to a growing understanding of the variety of ways in which pollution can affect wildlife populations, both acute and chronic, and direct and indirect (Peterson et al. 2003). Wildlife mortality has

been documented in association with many large oil spills (e.g., Flint et al. 1999, Goldsworthy et al. 2000, Munilla et al. 2011). Much of this mortality occurred in the days and weeks following these events, when freshly spilled oil is readily encountered by wildlife; we term this time period to be the “acute” phase of effects on wildlife. As indicated above, acute mortality of many wildlife species was observed after the EVOS. It is now recognized that acute mortality is only one of the ways in which oil spills can affect wildlife (Peterson et al. 2003). Effects expressed beyond the acute phase, which we refer to as “chronic” effects, can extend for months, years, or decades and, in some cases, may exceed the magnitude of acute mortalities (Iverson and Esler 2010, Monson et al. 2011). Chronic oil spill effects were not generally considered at the time of the *Exxon Valdez* event, but have been subsequently (Peterson et al. 2003).

Chronic effects of oil spills on wildlife can be manifested in a number of ways, including direct and delayed toxic effects, demographic lags, and indirect effects, which we review here.

Direct chronic effects occur due to toxic or thermoregulatory effects of exposure to oil after the acute phase. In the case of the EVOS, oil has persisted in the environment since the time of the spill (Short et al. 2004, 2006, Michel et al. 2010, Irvine et al. 2014). This “lingering oil” represents a tiny fraction of the spilled oil, but occurs in a largely unweathered state in subsurface sediments of beaches with certain physical characteristics that sequester the oil (Michel et al. 2010; see Esler et al., this report). Lingering oil presumably declines in occurrence, extent, and toxicity over time; however, studies indicate that several wildlife species were exposed to lingering oil over years to decades (see below). Although exposure to lingering oil does not necessarily imply subsequent effects (Lee and Anderson 2005), it does allow for the possibility of direct chronic effects; in the case of the EVOS, evidence for some species indicated that these direct effects occurred (see below).

Delayed toxic effects are consequences of oil exposure that are not expressed until months, years, or decades after that exposure. Oil ingestion can cause immune suppression, damage to genetic material, damage to a suite of organ systems, and oxidative stress. The effects of these might not be fatal to the affected animal until long after the exposure has ceased, via tumor formation, organ failure, or reductions in disease resistance (e.g., Miles et al. 2012). Also, toxic effects may act synergistically with natural stressors, with the combined cumulative effects leading to mortality (Holmes et al. 1979). Premature death as a result of delayed toxic effects could have significant effects on wildlife population dynamics (Monson et al. 2011).

Chronic effects also result from demographic lags, i.e., the time it takes for populations to return to conditions that would have existed in the absence of the spill, after direct oil effects have ceased. In other words, there are constraints on how fast populations can increase in abundance and these can delay recovery. The importance of demographic lags depends on a number of species-specific factors, including maximum reproductive potential, rates of dispersal, population structure, and other factors influencing density dependence. However, it is clear that immediate recovery did not occur following cessation of direct survival effects of the EVOS for a number of taxa and demographic lags were undoubtedly involved to some degree (Matkin et al. 2008, Iverson and Esler 2010, Monson et al. 2011).

Finally, chronic effects can result from indirect effects that can take a number of forms. Generally, indirect effects refer to oil spill-induced changes to the environment that, in turn, have deleterious consequences for wildlife. These could result from changes in prey availability or predator abundance, for example, or from other cascading effects that occur upon disruption of complex food webs (Peterson et al.

2003). Indirect effects related to EVOS-induced changes to prey availability have been implicated as a contributing factor constraining recovery for some taxa (Golet et al. 2002) but rejected for others (Dean et al. 2002, Esler et al. 2002).

Review of recovery timelines across wildlife species

In this section, we introduce a suite of species that exemplify variation in injury and recovery timelines (Fig. 1) and in the following section discuss varying mechanisms and degrees of effects of the oil spill. Different wildlife species have different vulnerabilities to the suite of potential effects of oil spills described above. Those vulnerabilities are influenced by life history characteristics, such as generation times, reproductive potential and natural survival rates, along with natural history characteristics, such as habitat use, diet, and foraging behavior. Given the diversity of wildlife species occurring in marine habitats of the northern Gulf of Alaska, it is not surprising that effects of the EVOS varied. In this section, we consider a suite of species that exemplify the varying mechanisms and degrees of effects of the oil spill, with resulting variation in injury and recovery timelines (Figure 5-2).

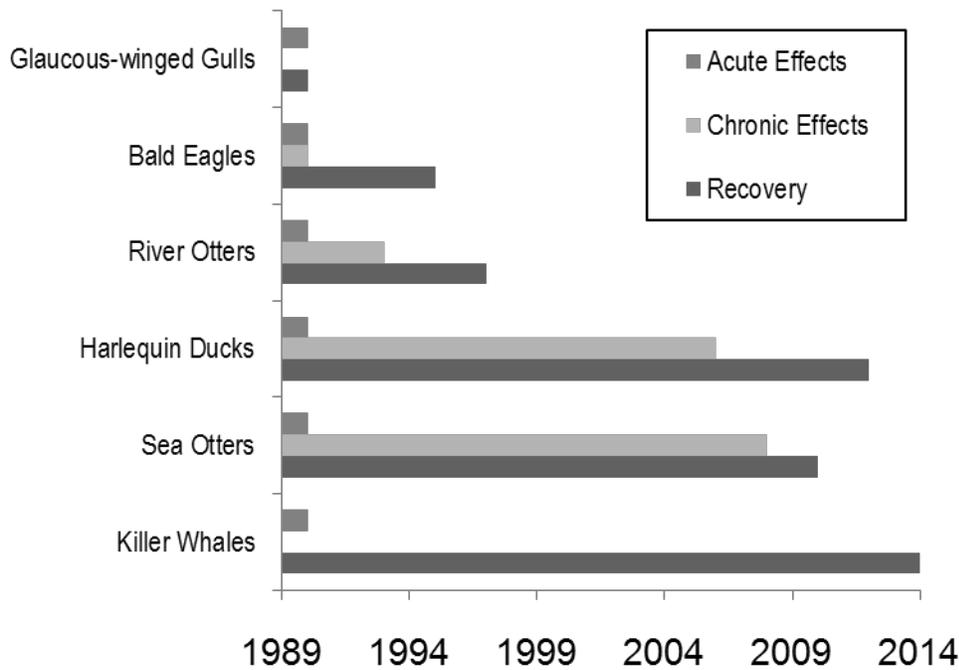


Figure 5-1. Examples of timelines of injury and recovery of selected species following the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska.

Glaucous-winged gulls (*Larus glaucescens*) are representative of species for which relatively small numbers of acute mortalities were detected (Piatt et al. 1990). Densities may have been depressed during the year of the spill, but no chronic injury or lack of recovery was evident (Day et al. 1997, Irons et al. 2000, Cushing et al. 2012).

Bald eagles (*Haliaeetus leucocephalus*) experienced roughly 5% acute mortality in PWS and significantly reduced reproductive performance in oiled areas during 1989, the year of the spill (Bowman et al. 1997).

However, no differences in survival or reproduction were observed in subsequent years (Bowman et al. 1995), and bald eagles were considered to have recovered by 1995 based on return to pre-spill numbers.

River otters (*Lontra canadensis*) in oiled areas expressed values for a variety of biomarkers indicative of poor health during the years immediately following the EVOS (1989 – 1992), presumably as a result of direct chronic exposure to oil (Bowyer et al. 2003). Habitat use, diet, and body mass also differed between river otters living in oiled and unoiled areas during that period. By the mid-1990s, many of these attributes had improved, and Bowyer et al. (2003) concluded that river otters had recovered by 1997.

Harlequin ducks have been intensively studied since the spill. Several lines of evidence indicate direct chronic injury and protracted recovery. Densities were lower in oiled areas than expected through 1997, after accounting for habitat attributes (Esler et al. 2000a). Also, adult female survival in oiled areas was depressed up to a decade following the spill (Esler et al. 2000b), coincident with biomarker evidence of exposure to lingering oil (Trust et al. 2000). By 2003, survival rates had returned to normal, despite continued oil exposure (Esler and Iverson 2010). Demographic data were assembled in a population model, and the best estimate of time until full recovery was 24 years post-spill, or 2013, due in part to demographic lags (Iverson and Esler 2010). However, biomarker data indicated that harlequin ducks continued to be exposed to oil through at least 2009 (Esler et al. 2010). Recent findings indicate lack of exposure to oil by 2013 (see below) and hence recovery from effects of the spill.

Sea otters are another species for which exposure to lingering oil led to direct chronic effects. Population models were developed to determine the timeline and spatial extent of mortalities related to chronic effects of the *Exxon Valdez* spill, using age distributions of living and dead otters and spatially-explicit population trend data (Monson et al. 2000, 2011). These models indicated that mortality rates were higher in areas affected by lingering oil until at least 2005, at which point survival effects began to dissipate. These findings are consistent with sea otter survey data since the spill, which showed depressed numbers in heavily oiled areas through 2009. The most recent findings indicate mortality patterns and abundance have returned to pre-spill conditions (see below).

Killer whales (*Orcinus orca*) suffered acute mortalities in both a resident and transient pod that occur in PWS (Matkin et al. 2008, Matkin et al., this report). Neither of these pods has recovered to pre-spill numbers, although it is unlikely that exposure to lingering oil is leading to chronic direct effects. Killer whale recovery is constrained by demographic factors associated with life history characteristics and small population size. Timeline to recovery for this species is unknown, and it is possible that the transient pod will never recover (Matkin et al., this report).

Factors related to recovery timelines

As indicated above, mechanisms leading to oil spill injury and timelines to population recovery vary widely among wildlife species. In the acute phase of oil spills, wildlife that spend much of their time on the ocean surface are particularly vulnerable to direct spill effects (Piatt et al. 1990, Goldsworthy et al. 2000), as that is where much of the oil occurs. For example, killer whales were observed surfacing in oil slicks (Matkin et al. 2008). In the chronic phase, much of the bioavailable oil is found in intertidal habitats, so wildlife that use those habitats are more likely to be exposed to oil and therefore to be subject to direct chronic effects of exposure. In the case of the *Exxon Valdez* spill, wildlife utilizing intertidal habitats showed chronic exposure, chronic direct effects of oil, or both. These included river otters (Bowyer et al. 2003), harlequin ducks (Esler et al. 2002, 2010), and sea otters (Bodkin et al. 2002, Dean et

al. 2002, Monson et al. 2011, Bodkin et al. 2012), mentioned above, as well as pigeon guillemots (*Cephus columba*; Golet et al. 2002), black oystercatchers (*Haematopus bachmani*; Andres 1999), and Barrow's goldeneyes (*Bucephala islandica*; Esler et al. 2011).

In addition to habitat use, diet also can influence vulnerability to oil exposure during the chronic phase of oil spills, and thus likelihood of injury and delayed population recovery. In the case of the *Exxon Valdez* spill, wildlife that consume benthic invertebrates were more likely to be exposed to oil and subject to chronic direct effects (Peterson and Holland-Bartels 2002). There may be multiple reasons for this; first, wildlife consuming benthic invertebrates are foraging on, and in some cases digging into, sediments that may contain lingering oil (Bodkin et al. 2012). Second, invertebrate prey, particularly filter feeders, may accumulate hydrocarbons (Fukuyama et al. 2000, Thomas et al. 2007) that, once consumed, may lead to detrimental effects on the wildlife consumers. Species consuming vertebrate prey (e.g., fish), such as river otters (see above), may be less vulnerable to prey-mediated exposure, as vertebrate prey are not likely to accumulate hydrocarbons because they possess physiologic mechanisms capable of metabolizing and eliminating hydrocarbons..

Wildlife species also vary in their thermal or metabolic sensitivity to oil exposure. For example, during the acute phase of the EVOS, sea otters were considered to be more vulnerable than other marine mammals to effects of external oiling, due to their reliance on their fur for insulation and lack of a substantial blubber layer (Ballachey et al. 1994). Birds in cold water environments are known to be highly susceptible to hypothermia when their insulation is compromised due to feather oiling (Jenssen and Ekker 1991). External oiling also is possible during the chronic phase of oil spills, if oil sequestered in the environment is released through disturbance of sediments by storms or foraging animals (Bodkin et al. 2012). Wildlife species also may be metabolically sensitive to effects of oil exposure due to naturally high metabolic rates (e.g., sea otters, Bodkin et al. 2002) or little scope to accommodate additional energetic costs due to oil exposure (e.g., harlequin ducks, Esler et al. 2002).

Life history characteristics also influence recovery times of wildlife to perturbations, including those of oil spills. Species with high reproductive rates and short generation times will recover more quickly than those with life histories oriented towards long life spans. As the extreme example in the case of the EVOS, recovery of the AB resident pod of killer whales has still not occurred over 25 years after the initial, acute mortality (Matkin et al. 2008, Matkin et al., this report).

Updates on recovery status of sea otters and harlequin ducks

As indicated above, sea otters and harlequin ducks were among the species with the most protracted recovery times following the EVOS, with lingering oil implicated as the primary constraint to full recovery. This resulted from their combination of characteristics that led to increased vulnerability to spill effects, including use of intertidal habitats where oil persisted, consumption of benthic invertebrates, and life histories constraining population growth potential (Peterson and Holland-Bartels 2002). For both species, lack of recovery was linked to direct chronic effects of exposure to residual oil and, in 2010, the EVOSTC considered sea otters and harlequin ducks to be recovering but not fully recovered. Recent data, collected as part of Gulf Watch Alaska, provide new insights on the recovery timeline of sea otters and harlequin ducks, and the EVOSTC declared both species recovered in 2014 (*Exxon Valdez* Oil Spill Trustee Council 2014).

Sea otter abundance

Recent sea otter data are presented and interpreted by Ballachey et al. 2014; we briefly summarize key findings here. Since 1993, sea otter abundance has been quantified based on aerial survey methods (Bodkin and Udevitz 1999) throughout western PWS, including the northern Knight Island archipelago, where heavy oiling resulting in strong acute and chronic effects on otters and, thus, where recovery was most delayed. Pre-spill numbers at northern Knight Island were estimated as the number of living animals observed in, as well as the number of carcasses recovered from, the northern Knight Island survey area (Dean et al. 2000).

Sea otter abundance in western PWS has been increasing since shortly after the oil spill (Ballachey et al. 2014), likely reflecting recovery from mortalities as a result of the oil spill; however, comparable estimates from before the spill are not available at this spatial scale. At northern Knight Island, sea otter abundance was below estimated pre-spill abundance through 2009, 20 years after the *Exxon Valdez* spill (Figure 5-3). However, in the 3 most recent years of surveys (2011, 2012, and 2013), abundance was similar to the pre-spill estimate (Figure 5-3). Given that northern Knight Island likely represents a “worst-case scenario” in terms of sea otter recovery, these recent data are an encouraging sign that sea otter status in PWS met the recovery criteria set by the EVOSTC, and in 2014 sea otters were declared recovered (*Exxon Valdez* Oil Spill Trustee Council 2014).

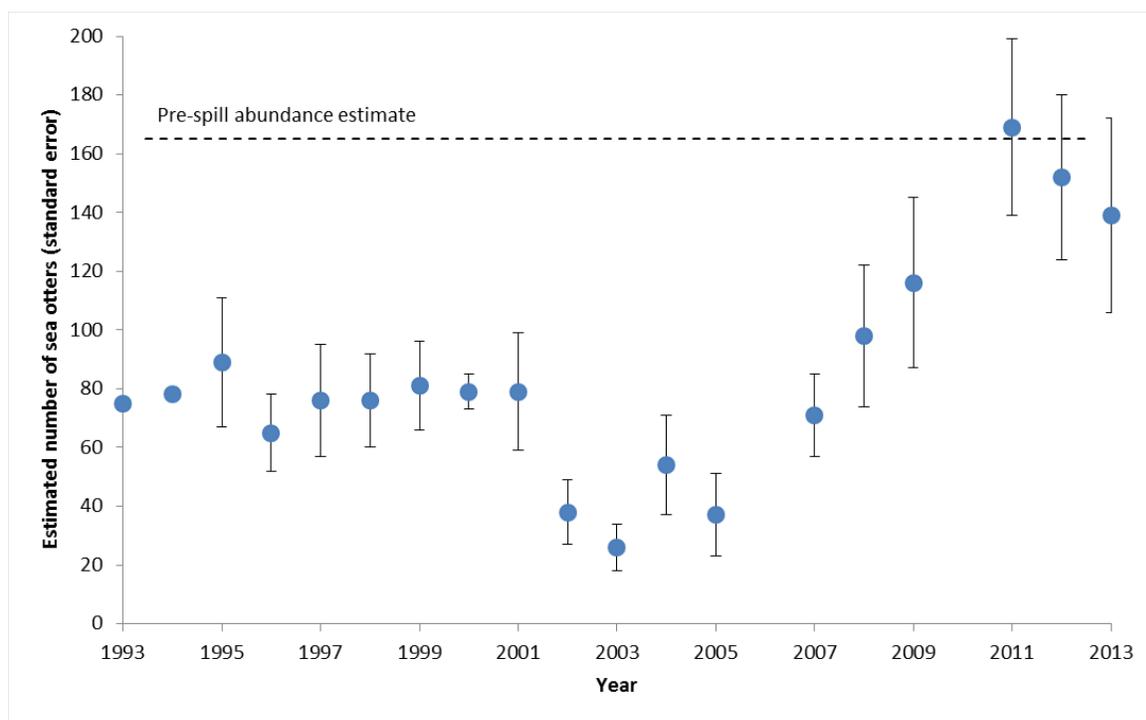


Figure 5-2. Estimated numbers of sea otters (\pm standard error) at heavily oiled northern Knight Island, Prince William Sound, Alaska, 1993–2013 relative to a pre-spill abundance estimate (from Ballachey et al. 2014).

Sea otter age distribution at death

The age distribution of sea otter carcasses recovered from beaches in western PWS each spring has proven to be an important gauge of population status (Monson et al. 2000, 2011). Discovered carcasses

are assumed to be representative of mortality patterns in the population. Teeth are extracted from carcasses to assign age, based on cementum layers.

Under normal conditions, mortalities in sea otters, like most other long-lived mammals, are concentrated in the youngest (0-1 years) and oldest (> 8 years) age classes. This pattern is evident in data from western PWS collected prior to the EVOS (Figure 5-4). However, during the year of the spill (1989) and the subsequent 20 years, a different pattern of mortality was evident, with higher proportions of prime-age (2-8 years) otters dying. This difference was interpreted as evidence of elevated mortality related to effects of oil exposure (Monson et al. 2000, 2011). However, in recent years (2010 to 2013), mortality patterns were similar to those expected under normal conditions and observed pre-spill (Figure 5-4). These data suggest that between 20 and 25 years after the spill direct chronic or delayed toxic effects of the EVOS were no longer causing sea otter mortality.

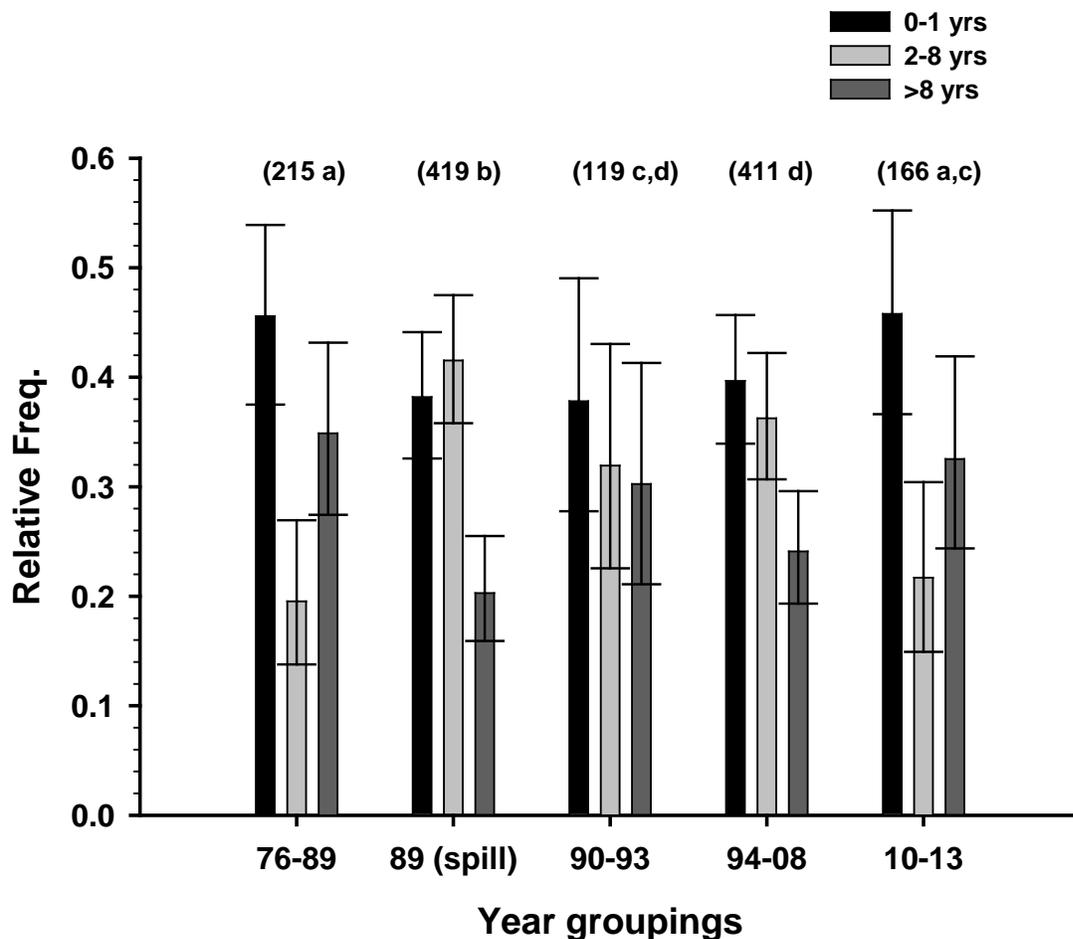


Figure 5-3. Relative age distributions of sea otter carcasses collected on western Prince William Sound beaches from 1976 to 2013. Total numbers of carcasses collected are in parentheses above each grouping and distributions with the same letter do not differ significantly from each other (from Ballachey et al. 2014).

Harlequin duck exposure to oil

Exposure to *Exxon Valdez* oil in harlequin ducks has been evaluated since 1998, through use of indicators of induction of members of the cytochrome P450 1 gene subfamily (CYP1A). Vertebrate CYP1A genes

are induced by exposure to hydrocarbons, including those found in crude oil, as well as a limited number of other compounds that do not occur in high concentrations in PWS (Ricca et al. 2010). This is a proven, sensitive, and specific biomarker of oil exposure. CYP1A is assayed via 7-ethoxyresorufin-O-deethylase (EROD) activity in liver biopsies surgically taken from captured harlequin ducks, and compared between oiled and unoled areas of PWS. In previous work (Trust et al. 2000, Esler et al. 2010), EROD activity was elevated in harlequin ducks from oiled areas through 2009 (Figure 5-5), which was interpreted as evidence of continued exposure to *Exxon Valdez* oil.

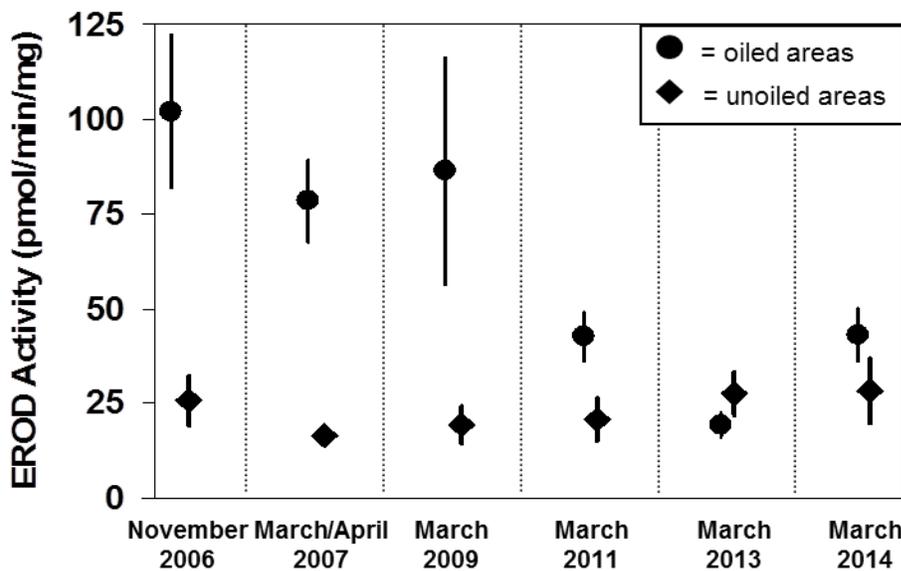


Figure 5-4. Average (\pm SE) hepatic 7-ethoxyresorufin-O-deethylase (EROD) activity (pmol/min/mg protein) of harlequin ducks captured in Prince William Sound, Alaska in March 2013 and 2014 ($n = 50$ each year), contrasted with results from previous years (Esler et al. 2010).

Recent data, including those collected as part of Gulf Watch Alaska, indicate reduction of exposure to lingering *Exxon Valdez* oil. In 2011, indices of CYP1A activity of harlequin ducks from oiled areas were lower than in previous years, although still statistically different from those in unoled areas (Figure 5-5). In 2013 and 2014, average EROD activity did not differ between harlequin ducks from oiled and unoled areas of PWS (Fig. 4). We interpret these data to indicate that exposure to lingering oil had largely ceased by 2013, 24 years after the EVOS.

Conclusions

The large amount of research on wildlife following the EVOS, including that conducted as part of Gulf Watch Alaska in recent years, led to unprecedented documentation of varying timelines of recovery and the opportunity to evaluate underlying constraints to recovery. This body of work resulted in some unexpected findings, including durations of recovery that were measured in decades for some species. Also, chronic exposure to oil persisting in intertidal sediments had stronger effects than anticipated, including effects that outweighed acute mortality in some species. Recent data indicate that two species that had protracted recovery, sea otters and harlequin ducks, have recently met the recovery criteria of the

EVOSTC, and both were declared recovered in 2014 (*Exxon Valdez* Oil Spill Trustee Council 2014). The results from this body of work have important implications for considerations of wildlife effects resulting from other oil spills, including the need for understanding chronic, demographic and ecosystem effects, to achieve a full accounting of the magnitude and timeline of wildlife losses. Also, the variety of constraints on recovery, which differ by species, offers generalizable insights for risk assessment and recovery planning.

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