



REPLY COMMENT

Quantifying long-term risks to sea otters from the 1989 'Exxon Valdez' oil spill: Reply to Harwell & Gentile (2013)

Brenda E. Ballachey*, James L. Bodkin, Daniel H. Monson

US Geological Survey, Alaska Science Center, 4210 University Drive, Anchorage, Alaska 99508, USA

ABSTRACT: Recovery of sea otter populations in Prince William Sound (PWS), Alaska, has been delayed for more than 2 decades following the 1989 'Exxon Valdez' oil spill. Harwell & Gentile (2013; Mar Ecol Prog Ser 488:291–296) question our conclusions in Bodkin et al. (2012; Mar Ecol Prog Ser 447:273–287) regarding adverse effects that oil lingering in the environment may have on sea otters. They agree that exposure may continue, but disagree that it constitutes a significant risk to sea otters. In Bodkin et al. (2012), we suggested that subtle effects of chronic exposure were the most reasonable explanation for delayed recovery of the sea otter population in areas of western PWS, where shorelines were most heavily oiled. Here, we provide additional information on the ecology of sea otters that clarifies why the toxicological effects of oral ingestion of oil do not reflect all effects of chronic exposure. The full range of energetic, behavioral, and toxicological concerns must be considered to appraise how chronic exposure to residual oil may constrain recovery of sea otter populations.

KEY WORDS: Sea otter · 'Exxon Valdez' · Oil spill · *Enhydra lutris* · Ecological risk assessment

Resale or republication not permitted without written consent of the publisher

Introduction

In Bodkin et al. (2012), we presented data describing frequency of intertidal foraging of sea otters in the northern Knight Island Archipelago (NKIA), an area of Prince William Sound (PWS), Alaska, that was heavily oiled in 1989 and where oil persists in intertidal sediments (Short et al. 2004, 2006, 2007). We concluded that between 2003 and 2005, individual sea otters were exposed to oil from 2 to 24 times per year. Our exposure rate estimates explicitly accounted for the probability of otters encountering oil at the tidal levels and on the substrates where oil occurred. Estimated exposure varied considerably among individuals, and all otters increased frequency of intertidal foraging during late spring and

early summer, a time when most adult females were nursing pups, which may be more vulnerable to effects of exposure to crude oil (Bodkin et al. 2012).

Based on the estimated frequency of encountering intertidal oil (and the presence of oil in foraging pits), we concluded that chronic exposure to lingering oil was delaying sea otter recovery. It was not possible to quantify the exposure, and biological and ecological effects of long-term exposure are difficult to resolve and remain largely unknown (Bodkin et al. 2012).

Harwell & Gentile (2013) agree with our conclusion that a pathway of exposure to lingering 'Exxon Valdez' oil exists and generally agree with our estimates of rates of encountering oil. However, they disagree with our conclusion that this exposure constitutes a significant risk to sea otters. Harwell &

*Email: bballachey@usgs.gov

Gentile (2013) reiterate results of their risk assessment model (Harwell et al. 2010), which accounted for exposure through ingestion of PAHs, and conclude that a toxicological response by sea otters to chronic oiling is implausible and therefore lack of recovery of sea otters at Knight Island cannot be attributed to lingering oil.

Assessment of risk for wild animals is complicated, however, as exposure to toxins is but one of many stressors faced by individuals, and these stressors may have synergistic interactions, resulting in cumulative effects that may extend well beyond those reflected by end points measured under controlled laboratory conditions with limited duration of exposure. Laboratory studies do not embody cumulative effects of lifetime toxin exposure, which in combination with other environmental stressors will elevate the ecological risk (see also Peterson et al. 2003). Furthermore, exposure to a combination of multiple PAHs and the unresolved complex mixture (UCM) fraction (Bodkin et al. 2012) may enhance toxicity, from interacting effects among compounds and with the natural environment (Laskowski et al. 2010, Silins & Högberg 2011) and from the many unidentified UCM compounds (Scarlett et al. 2007).

Here we describe adaptations and behaviors of wild sea otters that contribute to the risk of adverse effects from chronic exposure, with possible population level effects that may have contributed to the observed lack of full recovery over 2 decades (Bodkin et al. 2011). These additional risk factors are not included in the laboratory-based exposure models considered in Harwell et al. (2010) or Harwell & Gentile (2013).

External oiling

Deleterious physiological effects of external oiling on sea otters are well documented (Costa & Kooyman 1982, Siniff et al. 1982, Davis et al. 1988, Williams et al. 1988, 1995). Oil contamination of sea otter pelage will vitiate its water repellence and impair its thermoregulatory function; this results in hypothermia, which is physiologically costly in cold aquatic habitats.

In experimental oiling of 11 to 25% of a sea otter's pelage with 35 to 60 ml of crude oil, Costa & Kooyman (1982) documented an average decline in subcutaneous body temperature of 8.8°C and a 40 to 120% elevation in oxygen consumption. One animal in 5 died 11 d after 1 experimental oiling and washing (Costa & Kooyman 1982). Results of these experi-

ments are conservative, as otters were washed following experimental oiling and provided with plentiful food.

Based on studies of lingering oil in intertidal sediments at NKIA, wild sea otters occasionally will have encountered volumes of oil similar to experimental levels (Short et al. 2004). Additionally, animals in the wild will not be washed, must acquire their own food, and ambient air and water temperatures are lower in Alaska than they were in California, where the experiments were conducted. Even with lesser levels of contamination, there would be a metabolic cost.

Harwell et al. (2010) recognize the potential for external oiling of pelage, and include it in their model as a source of ingested PAHs, via grooming, but do not consider associated energetic costs. As demonstrated by Costa & Kooyman (1982) and supported by observations after the 'Exxon Valdez' spill (Williams et al. 1995), however, relatively minor external oiling, left untreated, contributes to morbidity and mortality in sea otters.

Energetic costs of altered activity

Sea otters live on a strict energy budget with little plasticity for unanticipated energetic costs (Yeates et al. 2007), especially at northern latitudes where thermal conditions are most challenging. In Alaska, sea otters spend 9 to 12 h d⁻¹ foraging, 11 to 12 h d⁻¹ resting, and 2 to 3 h d⁻¹ in other behaviors such as traveling and grooming (Garshelis et al. 1986, Bodkin et al. 2007, Esslinger et al. 2011). Experimental studies demonstrated increased grooming and elevated basal metabolic rates in otters exposed to relatively small amounts of external oil (Costa & Kooyman 1982, Siniff et al. 1982, Davis et al. 1988).

Chronic exposure to oil will require increased grooming, as it is essential to maintain insulative properties of the pelage. This will affect the overall activity budget, with a reduction in either resting or foraging time. The energetic burden of restoring contaminated fur is unknown but will be costly, because grooming ranks with surface swimming as the most energetically demanding of sea otter behaviors (Yeates et al. 2007).

Behavioral and demographic responses

Sea otters display dietary specialization (Tinker et al. 2007, 2008) and occupy small home ranges, on the order of a few km to a few tens of km of shoreline

(Garshelis et al. 1984, Jameson 1989, Ralls et al. 1996, Estes et al. 2003). Lingering 'Exxon Valdez' oil in PWS is aggregated in intertidal habitats that were heavily oiled in 1989 (Short et al. 2004, 2006, 2007), and coincides with the area where sea otter recovery has been delayed (Bodkin et al. 2011).

The extent to which sea otters avoid oiled habitats is unknown. Otter foraging pits were equally frequent on oiled and unoiled beaches in western PWS, suggesting avoidance may be minimal (Bodkin et al. 2012). However, if otters avoid oil, then longer-term behavioral modifications may include social disruption, permanent relocation away from oiled shorelines, and utilization of alternative foraging habitats or prey species, as availability of the species and habitats they prefer is restricted by contamination. Females with small pups may be affected disproportionately, as levels of intertidal foraging are high during the post-parturition period (Bodkin et al. 2012). Thus while avoidance would reduce exposure potential, it also could be associated with increased energetic costs that may adversely affect survival and ultimately population growth.

Furthermore, it is important to consider how sea otters recover from large-scale reductions in population abundance. At NKIA, where mortality approached 90% (Bodkin & Udevitz 1994), recovery presumably included recruitment of juveniles from adjacent areas, consistent with normal juvenile dispersal (Jameson 1989, Ralls et al. 1996). Juvenile sea otters rely heavily on intertidal forage species (Doroff & Bodkin 1994), elevating their exposure risk and contributing to low survival rates (Monson et al. 2000, 2011), in this case until sometime after 2003, when sea otter abundance began to recover (Bodkin et al. 2011).

Individual variation in exposure

Chronic exposure to lingering oil will not necessarily affect all individuals equally. Recently weaned sea otters forage in the intertidal more than adults, leading to greater oil exposure than we calculated based on our time-depth recorder data (Bodkin et al. 2012), which included adults and sub-adults (Age 3). Moreover, individual foraging strategies modify site-specific exposure (e.g. Johnson et al. 2009, Miller et al. 2010). Thus, there may be a bimodal distribution of exposure and of subsequent toxicological effects.

Temporal variation in exposure also contributes to differences among individuals. We found a higher frequency of foraging in the intertidal in late spring and early summer, possibly in response to greater

energetic content of intertidal prey (Esslinger et al. 2011). This coincides with a spring peak in pupping in PWS (Garshelis et al. 1984). Further, regardless of season, female sea otters with newborn pups forage to a greater extent in intertidal areas (USGS unpubl. data), increasing exposure to risk. Neonate sea otters stay with their mother and are entirely dependent on her for nourishment and grooming, so both will thus be more susceptible to adverse effects of external and internal oil exposure than independent individuals.

Conclusions

Harwell et al. (2010) concluded that there is no plausible risk of toxicological effects from oil exposure, but we find no plausible alternative to the conclusion that presence of lingering oil has been a constraint to recovery of species inhabiting nearshore areas that were heavily oiled in 1989 (Monson et al. 2000, 2011, Bodkin et al. 2002, Ballachey et al. 2003, 2011, 2012, Miles et al. 2012; see also Esler et al. 2002, 2010, 2011, Golet et al. 2002, Jewett et al. 2002, Thomas et al. 2007, Springman et al. 2008, Esler & Iverson 2010, Iverson & Esler 2010). Other explanations for population depression described by Harwell & Gentile (2013) do not adequately explain the spatial distribution of the observed effects.

We attribute the difference between Harwell et al. (2010) and our conclusions, at least in part, to the fact that they limited their assessment to oral ingestion of oil. We argue that toxicological effects and energetic costs of chronic exposure represent stressors that act synergistically with natural stressors in the environment to produce cumulative effects that cannot be duplicated in laboratory studies on which Harwell et al. (2010) based their model, whereas studies of sea otters and other species have provided ample evidence of demographic and biochemical differences between individuals in oiled versus unoiled areas since 1989.

Exposure has extended throughout the lifetime of individuals at risk, may have occurred through inhalation and transdermal absorption in addition to ingestion during foraging and grooming, and may have led to metabolic costs and behavioral alterations that reduced survival. Furthermore, the rates of ingestion modeled by Harwell et al. (2010) were based largely on data from 2002 and later, when exposure was diminishing and adverse effects of oil appeared to be moderating, which is consistent with the population recovery underway in sea otters (Bod-

kin et al. 2011) and sea ducks (Esler & Iverson 2010, Iverson & Esler 2010, Esler et al. 2010, 2011).

Finally, we reiterate the conclusions of Peterson et al. (2003) that, given delayed effects on multiple species following the 'Exxon Valdez' spill and continuing release of hydrocarbon pollutants into marine environments, (1) risk assessment modeling and estimation of natural resource injury need to be reconsidered, and (2) development of ecosystem-based toxicology is required to understand and ultimately predict chronic, delayed, and indirect long-term risks and effects.

Acknowledgements. This work was supported by the US Geological Survey, Ecosystems Mission Area, Wildlife Program, and the *Exxon Valdez* Oil Spill Trustee Council; however, the findings and conclusions do not necessarily reflect the views or position of the Trustee Council. We appreciate the support of H. A. Coletti, G. G. Esslinger, K. A. Kloecker, S. D. Rice and J. A. Reed, co-authors of Bodkin et al. (2012).

LITERATURE CITED

- Ballachey BE, Bodkin JL, Howlin S, Doroff AM, Rebar AH (2003) Correlates to survival of juvenile sea otters in Prince William Sound, Alaska. *Can J Zool* 81:1494–1510
- Bodkin JL, Udevitz MS (1994) Intersection model for estimating sea otter mortality along the Kenai Peninsula. In: Loughlin TA (ed) *Marine mammals and the Exxon Valdez*. Academic Press, San Diego, CA, p 81–95
- Bodkin JL, Ballachey BE, Dean TA, Fukuyama AK and others (2002) Sea otter population status and the process of recovery from the 1989 'Exxon Valdez' oil spill. *Mar Ecol Prog Ser* 241:237–253
- Bodkin JL, Monson DH, Esslinger GG (2007) Population status and activity budgets derived from time-depth recorders in a diving mammal. *J Wildl Manag* 71: 2034–2044
- Bodkin JL, Ballachey BE, Esslinger GG (2011) Trends in sea otter population abundance in western Prince William Sound, Alaska: progress toward recovery following the 1989 *Exxon Valdez* oil spill. USGS Sci Investig Rep 2011-5213, US Geological Survey, Reston, VA (available at <http://pubs.usgs.gov/sir/2011/5213/pdf/sir20115213.pdf>)
- Bodkin JL, Ballachey BE, Coletti HA, Esslinger GG and others (2012) Long-term effects of the 'Exxon Valdez' oil spill: sea otter foraging in the intertidal as a pathway of exposure to lingering oil. *Mar Ecol Prog Ser* 447:273–287
- Costa DP, Kooyman GL (1982) Oxygen consumption, thermoregulation, and the effect of fur oiling and washing on the sea otter, *Enhydra lutris*. *Can J Zool* 60:2761–2767
- Davis RW, Williams TM, Thomas JA, Kastelein RA, Cornell LH (1988) The effects of oil contamination and cleaning on sea otters (*Enhydra lutris*). II. Metabolism, thermoregulation, and behavior. *Can J Zool* 66:2782–2790
- Doroff AM, Bodkin JL (1994) Sea otter foraging behavior and hydrocarbon levels in prey. In: Loughlin TA (ed) *Marine mammals and the Exxon Valdez*. Academic Press, San Diego, CA, p 193–208
- Esler D, Iverson SA (2010) Female harlequin duck winter survival 11 to 14 years after the *Exxon Valdez* oil spill. *J Wildl Manag* 74:471–478
- Esler D, Bowman TD, Trust KA, Ballachey BE, Dean TA, Jewett SC, O'Clair CE (2002) Harlequin duck population recovery following the 'Exxon Valdez' oil spill: progress, process and constraints. *Mar Ecol Prog Ser* 241:271–286
- Esler D, Trust KA, Ballachey BE, Iverson SA and others (2010) Cytochrome P4501A biomarker indication of oil exposure in harlequin ducks up to 20 years after the *Exxon Valdez* oil spill. *Environ Toxicol Chem* 29: 1138–1145
- Esler D, Ballachey BE, Trust KA, Iverson SA and others (2011) Cytochrome P4501A biomarker indication of the timeline of chronic exposure of Barrow's goldeneyes to residual *Exxon Valdez* oil. *Mar Pollut Bull* 62:609–614
- Esslinger GG (2011) Temporal patterns in the behavior and body temperature of sea otters in Alaska. MS thesis, University of Alaska, Anchorage
- Estes JA, Riedman ML, Staedler MM, Tinker MT, Lyon BE (2003) Individual variation in prey selection by sea otters: patterns, causes and implications. *J Anim Ecol* 72: 144–155
- Garshelis DL, Johnson AM, Garshelis JA (1984) Social organization of sea otters in Prince William Sound, Alaska. *Can J Zool* 62:2648–2658
- Garshelis DL, Garshelis JA, Kimker AT (1986) Sea otter time budgets and prey relationships in Alaska. *J Wildl Manag* 50:637–647
- Golet GH, Seiser PE, McGuire AD, Roby DD, Fischer JB and others (2002) Long-term direct and indirect effects of the 'Exxon Valdez' oil spill on pigeon guillemots in Prince William Sound, Alaska. *Mar Ecol Prog Ser* 241:287–304
- Harwell MA, Gentile JH (2013) Quantifying long-term risks to sea otters from the 'Exxon Valdez' oil spill: Comment on Bodkin et al. (2012). *Mar Ecol Prog Ser* 488:291–296
- Harwell MA, Gentile JH, Johnson CB, Garshelis DL, Parker KR (2010) A quantitative ecological risk assessment of the toxicological risks from *Exxon Valdez* subsurface oil residues to sea otters at Northern Knight Island, Prince William Sound, Alaska. *Hum Ecol Risk Assess* 16:727–761
- Iverson SA, Esler D (2010) Harlequin duck population injury and recovery dynamics following the 1989 *Exxon Valdez* oil spill. *Ecol Appl* 20:1993–2006
- Jameson RJ (1989) Movements, home ranges, and territories of male sea otters off central California. *Mar Mamm Sci* 5:159–172
- Jewett SC, Dean TA, Woodin BR, Hoberg MK, Stegeman JJ (2002) Exposure to hydrocarbons ten years after the *Exxon Valdez*: evidence from cytochrome P4501A expression and biliary FACs in nearshore demersal fishes. *Mar Environ Res* 54:21–48
- Johnson CK, Tinker MT, Estes JA, Conrad PA and others (2009) Prey choice and habitat use drive sea otter pathogen exposure in a resource-limited coastal system. *Proc Natl Acad Sci USA* 106:2242–2247
- Laskowski R, Bednarska AJ, Kramarz PE, Loureiro S, Scheil V, Kudlek J, Holmstrup M (2010) Interactions between toxic chemicals and natural environmental factors — a meta-analysis and case studies. *Sci Total Environ* 408: 3763–3774
- Miles AK, Bowen L, Ballachey BE, Bodkin JL and others (2012) Variation of transcript profiles between sea otters *Enhydra lutris* from Prince William Sound, Alaska, and clinically normal reference otters. *Mar Ecol Prog Ser* 451: 201–212
- Miller MA, Kudela RM, Mekebrei A, Crane D and others (2010) Evidence for a novel marine harmful algal bloom:

- cyanotoxin (microcystin) transfer from land to sea otters. *PLoS ONE* 5:e12576
- Monson DH, Doak DF, Ballachey BE, Johnson A, Bodkin JL (2000) Long-term impacts of the *Exxon Valdez* oil spill on sea otters, assessed through age-dependent mortality patterns. *Proc Natl Acad Sci USA* 97:6562–6567
- Monson DH, Doak DF, Ballachey BE, Bodkin JL (2011) Could residual oil from the *Exxon Valdez* spill create a long-term population 'sink' for sea otters in Alaska? *Ecol Appl* 21:2917–2932.
- Peterson CH, Rice SD, Short JW, Esler D, Bodkin JL, Ballachey BE, Irons DB (2003) Long-term ecosystem response to the *Exxon Valdez* oil spill. *Science* 302:2082–2086
- Ralls K, Eagle TC, Siniff DB (1996) Movements and spatial use patterns of California sea otters. *Can J Zool* 74: 1841–1849
- Scarlett A, Galloway TS, Rowland SJ (2007) Chronic toxicity of unresolved complex mixture (UCM) of hydrocarbons in marine sediments. *J Soils Sediments* 7:200–206
- Short JW, Lindeberg MR, Harris PA, Maselko JM, Pella JJ, Rice SD (2004) Estimate of oil persisting on beaches of Prince William Sound, 12 years after the *Exxon Valdez* oil spill. *Environ Sci Technol* 38:19–25
- Short JW, Maselko JM, Lindeberg MR, Harris PM, Rice SD (2006) Vertical distribution and probability of encountering intertidal *Exxon Valdez* oil on shorelines of three embayments within Prince William Sound, Alaska. *Environ Sci Technol* 40:3723–3729
- Short JW, Irvine GV, Mann DH, Maselko JM and others (2007) Slightly weathered *Exxon Valdez* oil persists in Gulf of Alaska beach sediments after 16 years. *Environ Sci Technol* 41:1245–1250
- Silins I, Högberg J (2011) Combined toxic exposures and human health: biomarkers of exposure and effect. *Int J Environ Res Public Health* 8:629–647
- Siniff DB, Williams TD, Johnson AN, Garshelis DL (1982) Experiments on the response of sea otters *Enhydra lutris* to oil. *Biol Conserv* 23:261–272
- Springman KR, Short JW, Lindeberg MR, Maselko JM, Khan C, Hodson PV, Rice SD (2008) Semipermeable membrane devices link site-specific contaminants to effects: Part 1 — Induction of CYP1A in rainbow trout from contaminants in Prince William Sound, Alaska. *Mar Environ Res* 66:477–486
- Thomas RE, Lindeberg M, Harris PM, Rice SD (2007) Induction of DNA strand breaks in the mussel (*Mytilus trossulus*) and clam (*Protothaca staminea*) following chronic field exposure to polycyclic aromatic hydrocarbons from the *Exxon Valdez* spill. *Mar Pollut Bull* 54:726–732
- Tinker MT, Costa DP, Estes JA, Wieringa N (2007) Individual dietary specialization and dive behaviour in the California sea otter: using archival time–depth data to detect alternative foraging strategies. *Deep-Sea Res II* 54: 330–342
- Tinker MT, Bentall G, Estes JA (2008) Food limitation leads to behavioral diversification and dietary specialization in sea otters. *Proc Natl Acad Sci USA* 105:560–565
- Williams TM, Kastelein RA, Davis RW, Thomas JA (1988) The effects of oil contamination and cleaning on sea otters (*Enhydra lutris*). I. Thermoregulatory implications based on pelt studies. *Can J Zool* 66:2776–2781
- Williams TM, O'Connor DJ, Nielsen SW (1995) The effects of oil on sea otters: histopathology, toxicology and clinical history. In: Williams TM, Davis RW (eds) *Emergency care and rehabilitation of sea otters: a guide for oil spills involving fur-bearing marine mammals*. University of Alaska Press, Fairbanks, AK, p 3–22
- Yeates LC, Williams TM, Fink TL (2007) Diving and foraging energetics of the smallest marine mammal, the sea otter (*Enhydra lutris*). *J Exp Biol* 210:1960–1970

Editorial responsibility: Matthias Seaman, Oldendorf/Luhe, Germany; Charles Peterson, Morehead City, North Carolina, USA

*Submitted: June 27, 2013; Accepted: July 31, 2013
Proofs received from author(s): August 6, 2013*