A Tale of Two Spills: Novel Science and Policy Implications of an Emerging New Oil Spill Model

CHARLES H. PETERSON, SEAN S. ANDERSON, GARY N. CHERR, RICHARD F. AMBROSE, SHELLY ANGHERA, STEVEN BAY, MICHAEL BLUM, ROBERT CONDON, THOMAS A. DEAN, MONTY GRAHAM, MICHAEL GUZY, STEPHANIE HAMPTON, SAMANTHA JOYE, JOHN LAMBRINOS, BRUCE MATE, DOUGLAS MEFFERT, SEAN P. POWERS, PONISSERIL SOMASUNDARAN, ROBERT B. SPIES, CAZ M. TAYLOR, RONALD TJEERDEMA, AND E. ERIC ADAMS

The 2010 Deepwater Horizon *oil release posed the challenges of two types of spill: a familiar spill characterized by buoyant oil, fouling and killing organisms at the sea surface and eventually grounding on and damaging sensitive shoreline habitats, and a novel deepwater spill involving many unknowns. The subsurface retention of oil as finely dispersed droplets and emulsions, wellhead injection of dispersants, and deepwater retention of plumes of natural gas undergoing rapid microbial degradation were unprecedented and demanded the development of a new model for deepwater well blowouts that includes subsurface consequences. Existing governmental programs and policies had not anticipated this new theater of impacts, which thereby challenged decisionmaking on the spill response, on the assessment of natural resource damages, on the preparation for litigation to achieve compensation for public trust losses, and on restoration. Modification of laws and policies designed to protect and restore ocean resources is needed in order to accommodate oil drilling in the deep sea and other frontiers.*

Keywords: deepwater oil well blowout, natural resource damage assessment, ocean oil drilling policy change, sustaining public trust resources

The *Deepwater Horizon* (DWH) well blowout in the Gulf of Mexico represents a tale of two spills: the traditional shore-bound surface spill and the novel deep-ocean persistence of intrusions of finely dispersed (atomized) oil, gas, and dispersants. The discharge of oil and gas under high pressure at 1500-meter (m) water depth makes the DWH incident categorically different from all previous well-studied crude oil releases into the sea. Implementation of legislatively mandated natural resource damage assessment (NRDA) revealed serious gaps in the baseline information on deep-sea communities, their functioning, and their ecotoxicological vulnerability, which demonstrates a need to modify the laws and policies intended to sustain ecosystem services that are at risk from oil and gas drilling.

Before the DWH incident, the prevailing scientific model (figure 1a) of maritime oil behavior, fate, and exposure pathways and the consequent impacts on natural resources reflected a synthetic understanding of historical oil spills as occurring typically on the surface or in shallow, nearshore waters (NRC 2003). In traditional spills, crude oil rises rapidly to or remains at the sea surface, and gaseous hydrocarbons escape into the atmosphere with minimal residence time in the water column. Organisms that occupy or frequently encounter the sea surface, such as floating seabirds, can suffer high mortality rates (Piatt 1991). On landfall, this generally cohesive surface oil fouls intertidal and shallow subtidal habitats, which degrades ecosystem services by killing sensitive organisms, including key providers of structural habitat, such as salt-marsh macrophytes and mangroves (e.g., Jackson et al. 1989). Oil can persist when it is buried in anoxic, nutrient-limited sediments, where weathering is inhibited (Boufadel et al. 2010), leading to chronic biological exposures that can reduce production (Culbertson et al. 2008, Michel et al. 2009) or reproductive output and indirectly suppress the population recovery of exposed animals for decades (Teal and Howarth 1984, Bodkin et al. 2002, Culbertson et al. 2007, Esler and Iverson 2010) by depressing their fitness (Peterson 2001, Rice et al. 2001).

In stark contrast, the DWH blowout occurred in deep (1500 m) offshore waters, where a highly turbulent discharge of hot, pressurized oil and gas entrained cold seawater under

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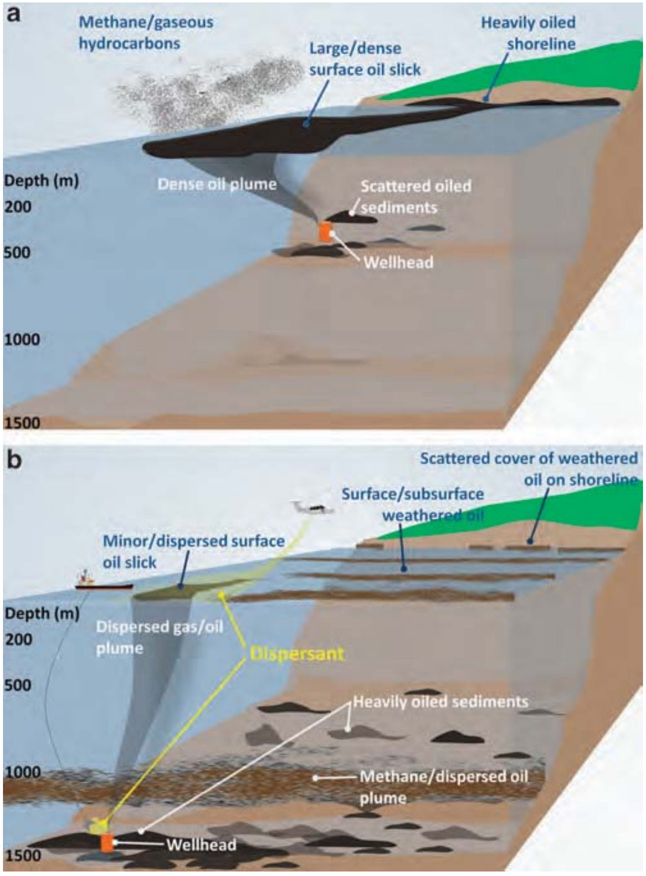

Figure 1. Contrast of (a) the traditional model for crude oil fate and effects that prevailed before the **Deepwater Horizon** *(DWH) blowout, based on synthesis of experience with nearshore maritime spills in shallow water, and (b) the newly emerging and still-developing model of a deepwater blowout like the DWH spill. Abbreviation: m, meters.*

high pressures and produced a variety of dispersed phases, including small oil droplets, gas bubbles, oil–gas emulsions, and gas hydrates. An injection of 0.77 million gallons of chemical dispersants at the wellhead, beginning 24 days after the well blowout, also contributed to the dispersion of the oil (Federal Interagency Solutions Group 2010). The collective buoyancy of the oil and gas created a rising plume, but unlike a continuous-phase (e.g., sewage) plume, much of the oil and gas separated from the entrained seawater as it apparently became trapped by depth-related physical discontinuities and was deflected laterally by ambient currents (Socolofsky et al. 2011). The dissolution into seawater of water-soluble petroleum compounds, including most of the methane, ethane, and propane and large fractions of water-soluble aromatic compounds, explains the elevated levels of petroleum hydrocarbons retained in the subsurface plume at a water depth of 1100 m (Reddy et al. 2012). A plume of hydrocarbon-enriched waters was observed by others at depths of 800–1200 m (Camilli et al. 2010, Valentine et al. 2010, Joye et al. 2011), at which hydrocarbons stimulated intense heterotrophic microbial activity (Kessler et al. 2011) and may have entered deep-sea food chains through pelagic primary consumers (as was exhibited by nearshore incorporation in mesozooplankton of petroleum carbon from DWH oil; Graham WM et al. 2010). The occurrence of a deepwater spill of this magnitude and with these characteristics is unprecedented and clearly warrants a new conceptual oil spill model (figure 1b). Although about half of the 4.9 million barrels of DWH oil did rise to the sea surface (Federal Interagency Solutions Group 2010), it became weathered during ascent, such that the oil reaching the surface appeared reddish-brown in color and was less cohesive than crude oil discharged onto the surface would be (figure 1a, 1b). Liquid oil droplets enriched with denser compounds, such as asphaltenes, descended toward the seafloor (Reddy et al. 2012). In addition, the process of the agglomeration of oil particles, sediments, drilling muds, and marine snow (detritus falling through the water column), mediated by adhesive bacterial exudates (Hazen et al. 2010), also triggered oil transport to the seafloor, where deposition of polycyclic aromatic hydrocarbon–enriched particulates appears to be associated with the death of hard- and soft-bottom invertebrates (figure 1b; Fisher 2010, Joye et al. 2011).

Although the DWH disaster breaks the prevailing mold of traditional shallow-water spills, the international petroleum industry has already transferred the focus of its marine exploration and production activities to deep (i.e., greater than 305 m) and ultradeep (i.e., greater than 500 m) fields, especially in the Gulf of Mexico, as nearshore shallow-water reservoirs have become depleted (Graham B et al. 2011). This redirection of ocean drilling in the oil and gas industry underscores the urgency to elaborate further details of the new oil spill model as a policy priority to prepare for future risk assessments and well blowouts (Jernelov 2010). Evaluating how massive the impacts of organic carbon loading, the taxon-dependent toxicity of multiple hydrocarbons and dispersants, and physical fouling are on a poorly understood pelagic and benthic deepwater ecosystem requires an enhanced scientific understanding.

The unexpected aspects and unknowns associated with deepwater ecosystems and the high-pressure petroleum releases during the DWH well blowout posed unanticipated challenges to the governmental response, which was dictated by federal legislation based on experience arising from traditional oil spills. In the United States, the Oil Pollution Act (OPA) of 1990 articulates policies that specify collaboration among federal, state, and tribal governments, together with the parties responsible for the oil spill, to assess impacts and achieve restoration. A sequence of actions implements those policies in the process known as NRDA (see Alexander 2010). NRDA is intended to achieve the following: (a) a minimization of environmental injury through emergency responses; (b) the use of defensible science to quantify damages to natural resources and their ecosystem and human services; (c) the provision through negotiation or litigation of a financial settlement sufficient to achieve compensatory restoration; and then (d) the implementation of restoration projects designed to replace losses of natural resources and of ecosystem services. The report of the presidential National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling (Graham B et al. 2011) documented many policy failings of the Minerals Management Service (MMS; now split into two independent agencies: the Bureau of Ocean Energy Management, and the Bureau of Safety and Environmental Enforcement), including, for example, the agency's failure to require in advance of deepwater drilling approval that drillers demonstrate the availability of tested technologies to terminate a deepwater blowout. Here, we document how and why the NRDA process is challenged by a well blowout in the deep sea and, by extension, other unfamiliar pollution events at environmental frontiers.

Emergency response

When a major oil release is detected, responders face difficult decisions on whether to choose or reject possible response actions. These choices are made by carefully weighing the potential benefits of the intervention against possible collateral harm, with the realization that intervention could cause more harm than good (Ritchie 1995). Assessing such trade-offs is made difficult by imperfect knowledge (Anastas et al. 2010) of both the effectiveness of the intervention and the risk of unintended damages. Mesocosm and laboratory experiments can provide useful insights, and some compelling experimental test designs have been developed and applied in the field following oil spills. For example, Mearns (1996) described the results of experiments in which the consequences of applying pressurized washing to oiled rocky intertidal communities fouled by *Exxon Valdez* oil were tested and that revealed that pressurized hot-water washing induces greater macroalgal and invertebrate mortality than the oiling itself.

Despite this advance in understanding the risks of pressurized washing of oiled rocky shores, during the 22 years since the *Exxon Valdez* oil spill, further progress in understanding the relative benefits and risks of harm for emergency interventions applicable to DWH spill response decisions has been limited. The major impediment to advancing such understanding is the failure of the existing policies and legislation to provide immediately accessible funding at the time of a major spill to support rigorous assessments of spill responses. The Mearns (1996) study, which serves as a model of capitalizing on the opportunities offered by a major spill, was funded outside the NRDA process by a government-monitoring program. Making use of opportunities for field testing of response effectiveness and for quantifying potential harm as a function of varying conditions should be included as an integral function of the NRDA process, so as to leave a legacy of enhanced preparedness in advance of the next oil spill. Providing sufficient funding for scientific studies of response effects could be incorporated into a revision of the OPA through, for example, expanding the Oil Spill Liability Trust Fund and modifying the corresponding NRDA policies to include the opportunity for the rapid funding of scientific studies of spill response.

The emergency responses (e.g., Lovett 2010) following the DWH blowout were diverse and applied intensively and extensively. Each response action that was taken had the potential to cause collateral biological injuries (table 1), many of which were confirmed by observations, even if they were not quantified by rigorous sampling designs. The most pervasive responses were applications of 1.07 million gallons of dispersants onto the sea surface and the unprecedented injection of 0.77 million gallons of dispersants directed toward petroleum jets escaping from the wellhead. The decision to employ dispersants on this scale involved evaluating trade-offs (NRC 2005, Federal Interagency Solutions Group 2010) and remains contentious, despite prior approval by the US Environmental Protection Agency (USEPA) and endorsement by a workshop of experts held weeks after the spill began. Dispersants were applied to weathered oil (mousse) at the sea surface during windy days with sufficient surface mixing to be effective, whereas on calm days, when dispersants are largely ineffective (Fingas 2001), mechanical skimming was the response of choice. Nevertheless, much dispersant still remained in near-surface waters from the previous applications during windier conditions, and much persisted with a long half-life in the deep sea (Kujawinski et al. 2011). The turbulent mixing induced by the pressurized discharge of hot oil and gas into entrained cold seawater was sufficient by itself to induce massive dispersion of oil into fine droplets; the dissolution of water-soluble hydrocarbons; and the creation of emulsions of oil, gas, water, and gas hydrates (Johansen et al. 2003, Federal Interagency Solutions Group 2010). Examination of the BP videos suggests that dispersant injection at the wellhead may not have consistently delivered the chemicals into the turbulent oil plume, which renders its efficacy uncertain (Kujawinski et al. 2011). Consequently, the chosen response of dispersant application now credited with successfully dispersing the DWH oil (Federal Interagency Solutions Group 2010) may have only marginally augmented the high degree of natural oil dispersion while elevating biological exposures to toxicants. The USEPA conducted new tests of the acute, short-term toxicity to two standard laboratory test organisms for dispersants used or considered for use in DWH spill response and of combinations of dispersants and Louisiana sweet crude oil and confirmed only modest toxicity (Hemmer et al. 2011). Subsequent NRDA research projects are now addressing dispersants and dispersed oil toxicity following chronic exposures of pelagic organisms more representative of those exposed to dispersed oil in the ocean after the DWH spill. Such rigorous scientific tests of the presumed benefits and harms of feasible response alternatives must be conducted on other response actions (table 1) in order to facilitate informed policy decisions on future responses. In the absence of available funds provided through the OPA for conducting rapid field testing of response consequences, the opportunity following the DWH spill to collect rigorous

Table 1. Examples of intended benefits and potential collateral injuries from response actions following the Deepwater Horizon *oil release. Research is needed to quantify effectiveness and benefits as well as collateral injuries to improve decisionmaking on responses to future oil spills.*

Response	Intended benefits	Collateral injuries
Surface oil burning	Oil removal from the ocean	Health impacts to humans and wildlife from atmospheric soot and toxic organics such as dioxins; ash deposition on sea floor
Oil skimming	Oil removal from the ocean	Skimming up and killing sea-surface organisms
Berm construction	Blockage of oil from reaching natural shoreline habitats of high value	Dredging and filling that kills benthic invertebrates (prey of crabs, shrimps, and demersal fishes); luring sea turtles and shorebirds to nest on unstable, eroding berm shores
Beach excavation	The removal of buried oil and tar balls	Killing intertidal invertebrates (prey of surf fishes, crabs, and shorebirds); removing wrack (habitat of invertebrate prey for shorebirds); disturbing sensitive shorebird and seabird nesting areas by vehicular traffic on beaches; running over shorebird chicks
Sea turtle nest relocation	The transport of eggs away from Gulf beaches at risk of oiling	Risking imprinting of surviving female sea turtles to return to nest on a different coast, thereby reducing Gulf populations
Boom deployment	Prevention of oil from reaching marshes and other sensitive habitats	Physically damaging the marsh when booms break loose and waves drive them into the marsh; trapping of waterbirds in oiled areas
Freshwater diversion	Oil kept offshore and away from sensitive marsh habitat through manipulation of river flows	Killing oysters over wide areas by reducing salinity; introduction of Mississippi River contaminants, including excessive nutrients to marshes; modifying fish distributions
Dispersant addition at the sea surface and at the wellhead	Dispersion of oil into fine droplets to accelerate its degradation by enhancing microbial access; a reduction of the volume of oil reaching the sea surface and grounding on shoreline habitats	Adding another toxin to the sea; exposing marine organisms to more biologically available dispersed oil and dispersants (Corexit in two formulations), risking widespread mortality of pelagic and benthic organisms, as well as food web and ecosystem impacts; exposing human oil responders and wildlife to health risks

scientific information to guide future responses may well be lost. Collateral injuries to public trust resources caused by even well-justified response interventions require compensatory restoration under the OPA (Alexander 2010), which provides more incentive to support scientific assessments in advance of emergency decisionmaking.

Natural resource damage assessment

NRDA is not a scientific endeavor but, rather, a legally driven process that employs science as the vehicle to achieve the quantification of injury and to obtain funds for compensatory restoration. For a familiar shallow-water oil spill, NRDA works well because of the large numbers of precedent shallow-water spills that guide injury assessments and frame restoration. The novelty, however, of the DWH blowout produced unprecedented scientific challenges to prevailing ecotoxicological and oceanographic models, as well as to the limited ecological understanding of deepwater and deep benthic habitats and their functioning (e.g., Schrope 2011). This limited the capacity to initiate a timely and complete program of natural resource injury assessments. In addition, the OPA process requires cooperative decisionmaking between the governmental trustee organizations and the responsible party and mutual approvals of NRDA studies if the studies are to be funded up front by the responsible party. The legislative requirement for this collaboration in decisionmaking slows down the NRDA process and influences the choice and limits the scope of NRDA studies that are conducted. Government trustees can decide to use public funds within governmental agencies to support studies with which the responsible party does not concur, but this step is discouraged by the OPA policy of collaboration and by serious budgetary limitations. The MMS, the responsible federal oversight agency, could have required more-complete scientific studies of the ecology of the deep pelagic ocean and risks posed by finely dispersed oil at depth, but MMS did not possess or provide enough funding to ensure adequate preparation for deepwater blowouts (Graham B et al. 2011). The need to enhance our understanding of novel oil and gas behavior, such as that associated with the DWH oil spill, could in part have been anticipated from prescient field (Johansen et al. 2003) and laboratory (Socolofsky and Adams 2002) experiments. It is unclear why these studies failed to lead to the development of a new model of deepwater risks, but lax oversight by MMS and the complacency of both the regulators and the industry played a role (Graham B et al. 2011).

Several serious gaps in scientific understanding exist that inhibited the capacity of the NRDA process to determine the ecosystem impacts of the DWH well blowout and that may have prevented the collection of the information necessary to detail all the important damages to the deepwater pelagic and benthic resources and their ecosystem functions. First, detailed understanding of the physicochemical behavior of oil, gas, and dispersants when they are released under the environmental conditions that prevailed at the wellhead is incomplete. Second, knowledge of the transport and fate of oil and gas depends on the challenging task of coupling dynamic changes in buoyancy with accurate, real-time, three-dimensional physical circulation models of the ocean.

Third, quantitative measures of the dispersion of oil into fine droplets and the creation of subsurface oil–gas–water–gas-hydrate emulsions that, to some degree, resulted in seafloor deposition (Joye et al. 2011, Reddy et al. 2012) are needed in order to depict the fate of the released hydrocarbons and the extent of biological exposures. Such dispersion and subsurface retention of hydrocarbons probably accelerates microbial degradation (Kujawinski et al. 2011) yet simultaneously enhances exposure and magnifies injury to animals of the deep-sea water column and seafloor. Fourth, consequences for at-risk functional groups, such as particle feeders, are unclear, particularly at mesopelagic and bathypelagic depths, where baseline community characterization and functional biology are poorly documented. The taxon-specific toxicity (Lenihan et al. 2003) of hydrocarbons and dispersants must also be integrated into the understanding of biological oceanographic processes. The potentially important indirect and delayed consequences (Peterson et al. 2003) of impacts may include reductions in particle filtration capacity and prey availability to higher-order consumers (Hawkins and Southward 1992). Finally, the large subsidy of fixed carbon to the ocean ecosystem and the stimulation of heterotrophic microbial production present a conceptual challenge to biological oceanography. Microbially mediated biogeochemical cycling and the production of microbial biomass in the deep sea have yet to be fully integrated into our understanding of carbon flows into food webs that support the larger marine animals that are most valued by people.

Acknowledging that the greatest uncertainty over DWH spill injuries to natural resources arises from an incomplete appreciation of the new components of the oil spill model associated with deep subsurface oil fate and impacts (Schrope 2011), we examined how two federal rapid-response research programs allocated effort among habitats. We explicitly questioned how the study effort in each program was distributed among those habitats that were expected to have borne the brunt of the injuries on the basis of the traditional, shallow-water oil spill model versus those poorly characterized deepwater habitats that were also expected to be affected under the emerging deepwater blowout model (figure 1). The two funding programs are the initial set of NSF-funded Grants for Rapid Response Research (RAPID grants) and the initial set of oil spill NRDA damage assessment studies. Effort was estimated by total numbers of grants and fractions of grants allocated for studying a habitat. Each RAPID and NRDA project was scored for all habitats included in the study; the scores for grants covering more than one habitat were weighted (adjusted) by dividing by the number of habitats (e.g., a study that included five different habitats would be allocated 0.20 for each habitat, whereas a study that included only one habitat would be allocated 1.00 for that habitat). Using dollars spent as an alternative metric would not alter the general patterns for NSF RAPID grants because they were capped at a fixed maximum cost. Costs of NRDA studies in the initial round were unavailable for analogous assessment. Habitats studied were determined from project summaries.

We first separated the environment into 12 separate habitats (5 shoreline habitats, 4 pelagic habitats covering different depth ranges in the water column, and 3 benthic habitats differing by seafloor depth; figure 2). For each of two scenarios (a composite of diverse shallow-water oil spills and a deepwater blowout under high pressure), we estimated the relative degree of expected ecological impact by habitat. Expected ecological impact in each habitat (figure 2a) was estimated as *extent* × (*intensity* + *recovery time*), where the *extent* was categorized as 0 (<1% of habitat affected), 1 (1%–10% affected), 2 (11%–50% affected), or 3 (>50% affected); *intensity* (a function of dose and sensitivity) was categorized as 0 (none), 1 (<10% mortality), 2 (11%–50% mortality) or 3 (>50% mortality); and *recovery time* was categorized as 0 (less than 1 month), 1 (1 month to 1 year), 2 (1–5 years) or 3 (>5 years). These categorizations were established by consensus of all of the authors.

The results are intended to provide a semiquantitative template of how impact study effort might be expected to be reallocated away from shoreline habitats and into the deep pelagic and benthic habitats, assuming study efforts should be proportional to the anticipated severity of ecological impacts. A shift in the distribution of ecological effects among habitats is evident in figure 2a, with the expected severity of impacts shifting from shallow sea surface and marsh and mangrove habitats to deep water and benthic habitats. Both the NSF RAPID (figure 2b) and the NRDA (figure 2c) allocations of study effort reveal only a modest shift towards more subsurface pelagic investigation than would have been allocated for traditional shallow-water oil spills but very low effort allocated to benthic habitats at any ocean depth. One explanation for the retention of relatively high assessment effort on sea-surface and shoreline impacts is that ecosystem and human services are known to be high for these habitats, yet are relatively unknown or unappreciated in the deep sea. In addition, the limited availability of specialized research platforms such as minisubs, ROVs (remotely operated vehicles), and oceanographic vessels constrained scientific research capacity to launch more benthic studies in deep waters in response to the blowout. The degree to which the ocean science community did respond to put people and equipment in place, albeit with inadequate funding and gaps in scope, was actually quite remarkable.

Much more research is needed to provide the scientific capacity to assess impacts of deepwater blowouts. Pursuing such research will prove costly, complex, and demanding of limited research platforms and technology. Assessing impacts acting through food web modifications, persistence of toxicants, and biogeochemical transformations may require relatively long time frames as lagged indirect effects play out over multiple years (e.g., Peterson et al. 2003, Culbertson et al. 2008). Multiyear investments in research do not fit

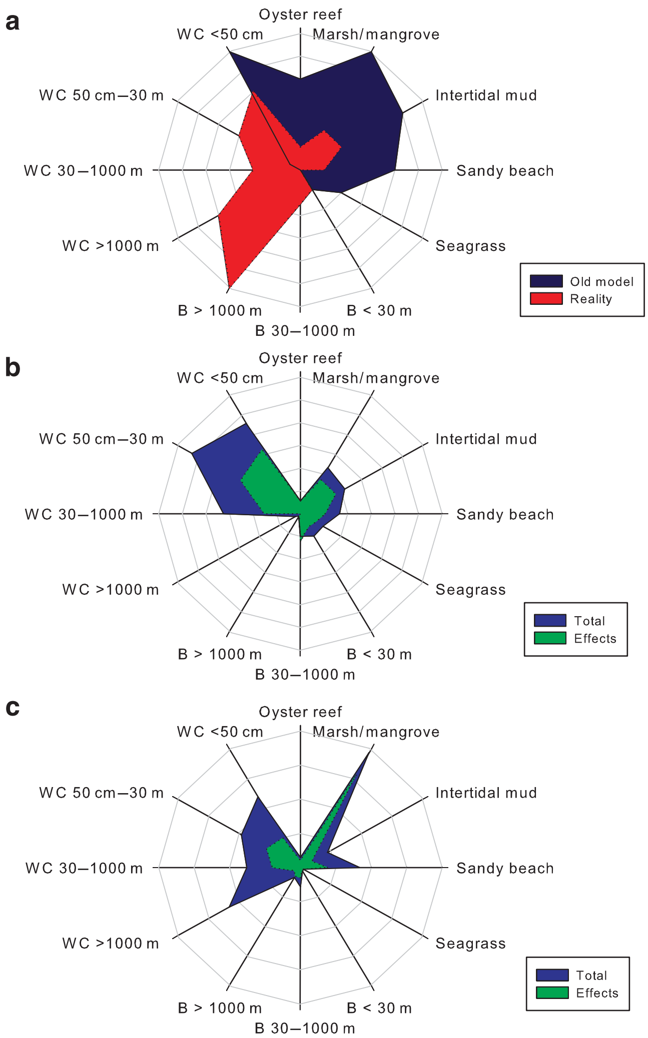

Figure 2. (a) Contrast of distributions of anticipated ecological effects of the Deepwater Horizon *oil spill among habitats under the old model (blue) and as realized under the newly evolving model (i.e., reality; red). Each ray of the diagram represents one habitat (B, benthic; WC, water column), with the distance from the center proportional to the projected impact. (b) Distribution of initial National Science Foundation RAPID awards among habitats, including all RAPID awards (blue), which includes studies of oil fate and other issues not directly related to spill effects, and only those awards focusing on ecological effects of the spill (green). Each ray of the diagram represents one habitat, with the distance from the center equal to the weighted total number of grants studying that habitat. (c) Distribution of initial government trustee-sponsored natural resource damage assessment (NRDA) studies among different habitats, including all NRDA studies (blue), some of which did not address habitat-explicit issues, and only those studies focused on the ecological effects of the spill (green). Each ray of the diagram represents one habitat, with the distance from the center equal to the weighted total number of studies of that habitat. Abbreviations: cm, centimeters; m, meters.*

comfortably within the traditional NRDA practices under the OPA, which contemplates familiar, more-accessible ecosystems of shallow waters and shorelines, where traditional approaches may suffice. A failure to take advantage of the DWH disaster as a massive, unplanned, and otherwise indefensible experiment would represent a missed opportunity to understand ecological and societal implications of this and future deepwater blowouts. Distributions of effort by two federal programs in assessing injury to natural resources (figure 2) do not suggest that sufficient attention was initially given to determining the fate of oil retained in the deep ocean or its impacts on deep water-column or benthic resources and basic ecosystem processes. Even if more effort were directed to these poorly known systems, the delay in committing to deepwater impact assessments may mean that the ecosystem response signals have been muted or masked, in which case, the full impacts of the subsurface retention of oil, gas, and dispersants will remain unknown and underestimated. Because of the potential scope of these deep-ocean impacts and the knowledge that oil and gas production has now shifted into the deep sea, the inability of the NRDA process to handle new scientific uncertainties on the scale exposed by the DWH disaster should not be used to justify a continuing failure to study and document deep-ocean injuries, which could perhaps be included as a part of a restoration project.

Implications for and of litigation

Strong incentives exist within the NRDA process for rapid settlement of monetary claims by governmental trustees of natural resources even before long-term direct and indirect damages may have been recognized (Peterson 2001, Peterson et al. 2003, Culbertson et al. 2007, 2008, Michel et al. 2009). Out-of-court settlements eliminate the high costs of trials, lead to earlier public disclosure of the types and magnitudes of damages discovered, and accelerate the implementation of compensatory restoration. Adopting a policy promoting efficient resolution of injury claims and reaching speedy settlement, however, may render moot the completion of the novel oil spill oceanography studies necessary to characterize the variety, scope, magnitude, and significance of deepwater impacts of the DWH spill. Compensation would then be based on a subset of natural resource damages, short-changing restoration of injured resources and diminishing capacity to anticipate and model likely risks and damages from future spills. Consequently, trustee decisionmakers face challenging trade-offs over whether to settle with the responsible parties quickly or only after delayed impacts have been revealed. Ideally, a quick settlement should include a reopener clause that can be activated and that specifies time limits for resolving reopener claims (unlike the restrictive conditions associated with the *Exxon Valdez* reopener; Alexander 2010), allowing compensation for injuries not yet recognized (striking the *Exxon Valdez* words "and not reasonably anticipated") at the time of settlement. It is hard to imagine a set of circumstances under which a more incomplete understanding of functioning and vulnerability to spilled oil exists than the deep-sea ecosystem affected by the DWH incident.

Restoration incapacity

Without completing studies of ecological functioning of deep-sea systems and pelagic and benthic impacts in the deep ocean, many natural resource impacts of the DWH blowout would probably remain unknown. These gaps in knowledge jeopardize reasonable implementation of compensatory restoration of those injured resources. The presently limited scientific appreciation of deep-sea food webs could lead to a conclusion that the biogeochemical interventions induced by massive injection of oil, gas, and dispersants into the deep sea and the mortalities of particle feeders from exposures to dispersed oil did not degrade delivery of ocean ecosystem services of value to humans. We view such a conclusion as presently unjustified. For example, 14 species protected under US laws and 39 more International Union for Conservation of Nature Red List species routinely use the spill area (Campagna et al. 2011), including sperm whales feeding on squid and other prey at depths as great as 1500 m. Such uses raise critical questions about whether the spill affected these valued species at risk by breaking the food chain links to particle feeders and thus to even higher trophic levels. Answers to such questions would educate present and future policymakers on the value of sustaining the integrity of deep-ocean functions and potential spill impacts on those processes. Conducting extensive science on deep-sea natural processes and on injuries to them does not fit into the narrow scope and short time frames of typical NRDA-driven damage assessment studies. Consequently, policy—and perhaps legislation (e.g., in the OPA)—changes are necessary to accommodate these needs and analogous events that were not anticipated from the composite model of familiar oil spills. One possible source of funding for these investigations could be restoration settlement funds, because the completion of compensatory restoration of the deep-sea damages is impossible without first knowing the extent of those damages. Compensatory restorations could include creating downward fluxes of natural organic particles by fertilizing the oligotrophic ocean surface with phosphate or by enhancing the *Sargassum*-associated community of fish and invertebrates by preventing commercial *Sargassum* harvests and by the introduction of cultured *Sargassum*—in each case, augmenting the downward fluxes of natural organic particles to particle feeders below. Either a failure to assess deep-sea injury or a failure to implement novel deep-sea restoration would induce partial restoration incapacity.

Implications for changing legislation and government policies

The ongoing implementation of NRDA in response to the DWH blowout is exposing critical information gaps, which collectively challenge the effective conduct of each successive phase of NRDA. NRDA depends on the preexistence of an adequate scientific understanding to produce compensatory restoration for lost resources and their ecosystem and human services. The scope and significance of the information gaps demonstrate that existing government programs and policies created to enforce key provisions of the National Environmental Policy Act (NEPA) were inadequate to protect natural resources and their services from oil spill injury arising in the deep ocean. Despite explicit requests by MMS for enhanced funding to conduct scientific tests of effectiveness and risks of alternative spill responses, Congress repeatedly failed to deliver sufficient support. The Outer Continental Shelf Lands Act (OCSLA) explicitly excluded the central and western Gulf of Mexico from the otherwise universal requirement to produce a development and production plan, which thereby reduced the levels of environmental review of oil-and-gas plans that are required elsewhere and which allowed deepwater drilling to proceed in those areas without the need for the information gathering that would allow a full assessment of risks (Graham B et al. 2011). The OPA was developed in 1990 to guide the NRDA process, but it used the *Exxon Valdez* oil spill for its model of risks of oil spill injuries and failed to anticipate the legitimate science needs and risks to environmental resources and their services in new frontiers such as deep water. This focus led to a failure to endorse the need for and to fund sufficient ecological, physical, and socioeconomic study to support an accurate risk assessment and to implement NRDA in frontier conditions that differ from the expectations of the traditional model. The OCSLA provides only 30 days for the US Department of the Interior (DOI) to complete a review of any exploration plan duly submitted by a leaseholder in the outer continental shelf of the Gulf. This time is insufficient to conduct an environmental impact study or even an environmental assessment, and therefore, the legislated short review time represents an implicit policy of encouraging a superficial environmental review, which would minimize the creation and use of scientific information on ecosystem risks (Alexander 2010). Through internal management decisions, since 1981, the DOI has exercised its option under the OCSLA to grant categorical exclusions to relieve most Gulf of Mexico drilling plans from NEPA review requirements (Graham B et al. 2011). For deep water, this practice would appear to violate the condition that most categorical exclusions must meet—namely, that even under the worst conditions, no negative environmental impacts would be expected. Although policy and legislative shortcomings have already led to inadequate information to facilitate a comprehensive NRDA in deep water after the DWH blowout, policy and legislative changes are still needed in advance of oil drilling in any frontier region, such as the Arctic, where the familiar oil spill model is also insufficient to guide NRDA.

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References cited

Alexander K. 2010. The 2010 Oil Spill: The Minerals Management Service (MMS) and the National Environmental Policy Act (NEPA). Report no. R41265. (29 February 2012; *http://fpc.state.gov/documents/organization/145106.pdf*)

Anastas PT, Sonich-Mullin C, Fried B. 2010. Designing science in a crisis: The *Deepwater Horizon* oil spill. Environmental Science and Technology 44: 9250–9251.

Bodkin JL, Ballachey BE, Dean TA, Fukuyama AK, Jewett SC, McDonald L, Monson DH, O'Clair CE, VanBlaricom GR. 2002. Sea otter population status and the process of recovery from the 1989 '*Exxon Valdez*' oil spill. Marine Ecology Progress Series 241: 237–253.

Boufadel MC, Sharifi Y, Van Aken B, Wrenn BA, Lee K. 2010. Nutrient and oxygen concentrations within the sediments of an Alaskan beach polluted with the *Exxon Valdez* oil spill. Environmental Science and Technology 44: 7418–7424.

Camilli R, Reddy CM, Yoerger DR, Van Mooy BAS, Jakuba MV, Kinsey JC, McIntyre CP, Sylva SP, Maloney JV. 2010. Tracking hydrocarbon plume transport and biodegradation at *Deepwater Horizon*. Science 330: 201–204.

Campagna C, Short FT, Polidoro BA, McManus R, Collette BB, Pilcher NJ, De Mitcheson YS, Stuart SN, Carpenter KE. 2011. Gulf of Mexico blowout increases risks to globally threatened species. BioScience 61: 393–397.

Culbertson JB, Valiela I, Peacock EE, Reddy CM, Carter A, VanderKruik R. 2007. Long-term biological effects of petroleum residues on fiddler crabs in salt marshes. Marine Pollution Bulletin 54: 955–962.

Culbertson JB, Valiela I, Pickart M, Peacock EE, Reddy CM. 2008. Long-term consequences of residual petroleum on salt marsh grass. Journal of Applied Ecology 45: 1284–1292.

Esler D, Iverson SA. 2010. Female harlequin duck winter survival 11 to 14 years after the *Exxon Valdez* oil spill. Journal of Wildlife Management 74: 471–478.

Federal Interagency Solutions Group. 2010. Oil Budget Calculator: *Deepwater Horizon*. Federal Interagency Solutions Group.

Fingas M. 2001. Dispersants. Pages 122–128 in Fingas M. The Basics of Oil Spill Cleanup, 2nd ed. CRC Press.

Fisher C. 2010. The final dive. National Oceanic and Atmospheric Administration. (29 February 2012; *http://oceanexplorer.noaa.gov/explorations/10lophelia/logs/nov3/nov3.html*)

Graham B, Reilly WK, Beinecke F, Boesch DF, Garcia TD, Murray CA, Ulmer F. 2011. Deep Water: The Gulf Oil Disaster and the Future of Offshore Drilling. National Commission on the BP *Deepwater Horizon* Oil Spill and Offshore Drilling.

Graham WM, Condon RH, Carmichael RH, D'Ambra I, Patterson HK, Linn LJ, Hernandez FJ Jr. 2010. Oil carbon entered the coastal planktonic food web during the *Deepwater Horizon* oil spill. Environmental Research Letters 5: 1–18.

Hawkins SJ, Southward AJ. 1992. The Torrey Canyon oil spill: Recovery of rocky shore communities. Pages 583–631 in Thayer GW, ed. Restoring the Nation's Marine Environment. Maryland Sea Grant College.

Hazen TC, et al. 2010. Deep-sea oil plume enriches indigenous oil-degrading bacteria. Science 330: 204–208.

Hemmer MJ, Barron MG, Greene RM. 2011. Comparative toxicity of eight oil dispersants, Louisiana sweet crude oil (LSC) and chemically dispersed LSC to two aquatic test species. Environmental Toxicology and Chemistry 30: 2244–2252. (29 February 2012; *http://dx.doi.org/10.1002/etc.619*)

Jackson JBC, et al. 1989. Ecological effects of a major oil-spill on Panamanian coastal marine communities. Science 243: 37–44.

Jernelov A. 2010. The threats from oil spills: Now, then, and in the future. Ambio 39: 353–366.

Johansen Ø, Rye H, Cooper C. 2003. DeepSpill—Field study of a simulated oil and gas blowout in deep water. Spill Science Technology Bulletin 8: 433–443.

Joye SB, MacDonald IR, Leifer I, Asper V. 2011. Magnitude and oxidation potential of hydrocarbon gases released from the BP well blowout. Nature Geoscience 4: 160–164.

Kessler JD, et al. 2011. A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. Science 331: 312–315.

Kujawinski EB, Soule MCK, Valentine DL, Boysen AK, Longnecker K, Redmond MC. 2011. Fate of dispersants associated with the *Deepwater Horizon* oil spill. Environmental Science and Technology 45: 1298–1306.

Lenihan HS, Peterson CH, Kim SL, Conlan KE, Fairey R, McDonald C, Grabowski JH, Oliver JS. 2003. Variation in marine benthic community composition allows discrimination of multiple stressors. Marine Ecology Progress Series 261: 63–73.

Lovett RA. 2010. Oil spill's toxic trade-off. Nature News 10 November 2010. (29 February 2012; *www.nature.com/news/2010/101110/full/news.2010.597.html*) doi:10.1038/news.2010.597

Mearns AJ. 1996. *Exxon Valdez* shoreline treatment and operations: Implications for response, assessment, monitoring and research. Pages 309–328 in Rice SD, Spies RB, Wolfe DA, Wright BA, eds. Proceedings of the *Exxon Valdez* Oil Spill Symposium, American Fisheries Society Symposium 18. American Fisheries Society.

Michel J, Nixon Z, Dahlin J, Betenbaugh D, White M, Burton D, Turley S. 2009. Recovery of interior brackish marshes seven years after the Chalk Point oil spill. Marine Pollution Bulletin 58: 995–1006.

[NRC] National Research Council. 2003. Oil in the Sea III: Inputs, Fates, and Effects. National Academies Press.

———. 2005. Oil Spill Dispersants: Efficacy and Effects. National Academies Press.

Peterson CH. 2001. A synthesis of direct and indirect or chronic delayed effects of the *Exxon Valdez* oil spill. Advances in Marine Biology 39: 1–103.

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.

Piatt JF, Lensink CJ, Butler W, Kenziorek M, Nysewander DW. 1990. Immediate impact of the *Exxon-Valdez* oil spill on marine birds. Auk 107: 387–397.

Reddy CM, et al. 2012. Composition and fate of gas and oil released to the water column during the *Deepwater Horizon* oil spill. Proceedings of the National Academy of Sciences. (29 February 2012; *pnas.org/cgi/doi/10.1073/pnas.1101242108*)

Rice SD, Thomas RE, Carls MG, Heintz RA, Wertheimer AC, Murphy ML, Short JW, Moles A. 2001. Impacts to pink salmon following the *Exxon Valdez* oil spill: Persistence, toxicity, sensitivity, and controversy. Reviews in Fisheries Science 9: 165–211.

Ritchie W. 1995. Maritime oil spills—Environmental lessons and experiences with special reference to low-risk coastlines. Journal of Coastal Conservation 1: 63–76.

Schrope M. 2011. Oil spill: Deep wounds. Nature 472: 152–154.

Socolofsky SA, Adams EE. 2002. Multi-phase plumes in uniform and stratified crossflow. Journal of Hydraulic Research 40: 661–672.

Socolofsky SA, Adams EE, Sherwood CR. 2011. Formation dynamics of subsurface hydrocarbon intrusions following the *Deepwater Horizon* blowout. Geophysical Research Letters 38 (Art. L09602). (29 February 2012; *www.agu.org/pubs/crossref/2011/2011GL047174.shtml*) doi:10.1029/2011GLO47174

Teal JM, Howarth RW. 1984. Oil spill studies: A review of ecological effects. Environmental Management 8: 27–43.

Valentine DL, et al. 2010. Propane respiration jump-starts microbial response to a deep oil spill. Science 330: 208–211.

Charles H. Peterson (cpeters@email.unc.edu) is a distinguished professor at the Institute of Marine Sciences, at the University of North Carolina at Chapel Hill, in Morehead City. Sean S. Anderson is an assistant professor in the Environmental Science and Resource Management Program at California State University Channel Islands, in Camarillo, California. Gary N. Cherr is a professor in the Departments of Environmental Toxicology and Nutrition and director of the University of California, Davis, Bodega Marine Laboratory, in Bodega Bay, California. Richard F. Ambrose is a professor in the Environmental Science and Engineering Program at the University of California Los Angeles. Shelly Anghera is the principal of Anchor QEA, L.P., in Mission Viejo, California. Steven Bay is a senior scientist with the Southern California Coastal Water Research Project, in Costa Mesa. Michael Blum and Caz M. Taylor are assistant professors in the Ecology and Evolutionary Biology Department at Tulane University, in New Orleans, Louisiana. Robert Condon is a marine scientist and Sean P. Powers is a senior marine scientist at the Dauphin Island Sea Lab, in Dauphin Island, Alabama. Monty Graham is a professor in and chairman of the Department of Marine Science at Southern Mississippi University at the Stennis Space Center. Thomas A. Dean is the president of Coastal Resources Associates, Inc., in Carlsbad, California. Michael Guzy is an assistant professor in the Biological and Ecological Engineering Department at Oregon State University, in Corvallis. Stephanie Hampton is the deputy director of the National Center for Ecological Analysis and Synthesis, in Santa Barbara, California. Samantha Joye is a distinguished professor in the Marine Sciences Department at the University of Georgia, Athens. John Lambrinos is an assistant professor in the Horticulture Department of Oregon State University, in Corvallis. Bruce Mate is a professor at the Oregon State University Hatfield Marine Science Center and director of the Marine Mammal Institute, in Newport, Oregon. Douglas Meffert is a professor in the Center for Bioenvironmental Research at Tulane University, in New Orleans, Louisiana. Ponisseril Somasundaran is a professor in the Center for Colloids and Interfaces at Columbia University, in New York, New York. Robert B. Spies is president of Applied Marine Science, in Little River, California. Ronald Tjeerdema is a professor in and chair of the Environmental Toxicology Department at the University of California, Davis. E. Eric Adams is a senior research engineer in the Civil and Environmental Engineering Department at the Massachusetts Institute of Technology, in Cambridge.