U.S. v. BP Exploration & Production, Inc. et al.

ACTUAL AND POTENTIAL HARM FROM THE MACONDO WELL BLOWOUT

Submitted on Behalf of the United States

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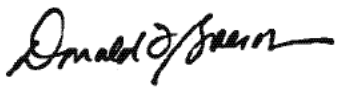

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1. SUMMARY CONCLUSIONS

The Macondo well blowout resulted in serious actual and potential harm to Gulf of Mexico ecosystems. The geographic scale of documented impacts was expansive: floating oil extended over at least 68,000 square miles and stranded on more than 1,138 miles of shoreline, including approximately 500 miles of wetland shores. Impacts on bottom-dwelling organisms around the wellhead extended over at least 57 square miles. While much information on the harm caused by the Macondo well blowout has been published in the scientific literature, significant research and the Natural Resources Damage Assessment are still underway, making it still too early to draw definitive conclusions. Nonetheless, existing information shows substantial actual harm was realized at least among:

(a) planktonic organisms and floating seaweed communities;

(b) deep seabed biota, including cold-water coral communities;

(c) moderately to heavily oiled coastal marsh and mangrove habitats; and

(d) birds, sea turtles and dolphins exposed to oil slicks.

There was potential harm to at least:

(a) bottom fishes living where hydrocarbons contaminated sediments;

(b) open-ocean fishes with larvae that develop near the sea surface; and

(c) biota inhabiting the seabed on the continental shelf in the vicinity of substantial floating oil.

(d) oyster stocks in areas affected by oil and related response actions.

These conclusions come with the caveat that other effects may yet occur or be revealed by further research and monitoring. The time scale of recovery—if recovery is possible—will vary depending on remaining contamination and the dynamics of affected populations. For marshes, cold-water corals and some bird and sea turtle species and bottlenose dolphins, this is likely to extend for years or decades into the future.

2. APPROACH

2.1. Expert's Background

This report was prepared by Dr. Donald F. Boesch, a Professor in the University of Maryland Center for Environmental Science. I am a coastal oceanographer with over 43 years of experience in research primarily along the U.S. Atlantic and Gulf coasts, but also along the coasts of Australia and China. This experience specifically includes investigations of the impacts of oil spills and offshore oil and gas development, the effects of land-based sources of pollution that are responsible for dead zones, and the causes and consequences of coastal wetland loss. I have decades of experience in the synthesis and application of scientific knowledge to inform policies and management practices for

the protection and restoration of large coastal ecosystems, including the Chesapeake Bay, coastal Louisiana, the greater Everglades and the Baltic Sea.

Beyond my own research, I assumed responsibilities for the administration of research and education programs early in my career when in 1980 I became the first Executive Director of the Louisiana Universities Marine Consortium (LUMCON). During the ten years I headed LUMCON, I was responsible for the design and construction of the DeFelice Marine Research Center at Cocodrie and two research vessels. The Research Vessel *Pelican* was the first research vessel on the scene after the Macondo well blowout and continues to be heavily employed in research on its effects.

For the past 24 years I have served as President of the University of Maryland Center for Environmental Science, overseeing a faculty of over 100 scientists based at four separate laboratories across Maryland, a position that requires a broad understanding across the environmental and social sciences. My extended service and background led to several prominent appointments, notably as a member of the Scientific Advisory Panel for the U.S. Commission on Ocean Policy and as Chair of the Ocean Studies Board of the National Research Council.

Although I have worked on many other subjects, my experience in evaluating the impacts of oil spills and offshore oil and gas production extends over my entire career. Following the 1969 well blowout in the Santa Barbara Channel off California I was commissioned by the Ford Foundation to produce a review of the scientific knowledge of effects of oil spills.[1] In the mid-1980s I led an assessment of the long-term effects of offshore oil and gas development activities under the auspices of a Federal interagency committee.[2] After the Exxon Valdez tanker spill in 1989, I advised the Federal-State Trustee Council on the Natural Resources Damage Assessment.

Because of these and other lifetime experiences in scientific assessment I was appointed by President Obama in 2010 as one of seven members of the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, which submitted its report to the President and Congress in early 2011.[3] The Commission was charged with determining the root causes of the accident and evaluating the adequacy of preventative regulations and responses to the Macondo blowout. The Commission did not assess actual or potential harm of the blowout.

2.2. Organization of Report

This assessment takes an ecosystem approach. An ecosystem is a community of organisms (plants, animals and microbes) in conjunction with the nonliving components of their environment, interacting as a system. In ecosystems the physical, chemical and geological environment affects

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[1] Boesch DF, Hershner CH, Milgram JH (1974) Oil Spills and the Marine Environment. Ballinger Pub. Co., Cambridge, MA114

[2] Boesch DF, Rabalais NN (1987) Long-term environmental effects of offshore oil and gas development. Elsevier Applied Science, New York, NY, USA

[3] National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011) DEEP WATER The Gulf Oil Disaster and the Future of Offshore Drilling U.S. Government Printing Office, Washington D.C.

the organisms and, conversely, the organisms affect the nonliving components of the environment as well as each other.

Figure 1. The portion of the Gulf of Mexico where most harm occurred, indicating the continental slope, continental shelf, and coastal ecosystems, including sounds and bays.

Following a brief reviews of toxic effects of Macondo well oil (Section 3) and the scale of the hydrocarbon contamination resulting from the Macondo well (Section 4), the impacts of the blowout on offshore ecosystems (Section 5) and coastal ecosystems (Section 6) are evaluated. Offshore ecosystems included the seabed and overlying waters of the continental slope, the relatively steeply sloped sea floor where the Macondo blowout occurred, the deeper abyssal plain, and the continental shelf (Figure 1).[4] Coastal ecosystems include those near shore and encompassing the beaches, bays and marshes of the Gulf Coast. Section 7 then draws general conclusions.

2.3. Reliance Materials

The report relies primarily on formal scientific literature. In developing the assessment and drawing conclusions I relied primarily on articles published in scientific journals. I have done so for several reasons:

(a) In contrast to less formally published reports that might present data and information, journal articles usually include descriptions of methods, present detailed results from analyses, and discuss findings in the context of the broader body of scientific knowledge.

(b) Most such articles were subjected to anonymous review by scientific peers and to requirements by editors designed to insure quality. While not verifying results and conclusions, peer-review and editing act to restrict the publication of unsupported results.

(c) Articles published in scientific journals are readily accessible to the scientific community, which evaluates, incorporates and challenges their results and conclusions.

As of March 13, 2014, after which it was no longer updated, the bibliography of published research and expert commentary related to Macondo well blowout maintained by the National Oceanic and Atmospheric Administration Central Library[5] included some 350 peer-reviewed journal articles

[4] Bouma AH, Roberts HH (1990) Northern Gulf-of-Mexico continental-slope. Geo-Marine Letters 10:177-181
[5] NOAA Central Library. Deepwater Horizon Bibliography. www.lib.noaa.gov/researchtools/subjectguides/dwh.html

and book chapters in the natural sciences, 20 in the medical sciences, and 202 in the social sciences. I relied on these and additional articles not included in the NOAA Central Library bibliography.

Many additional results have been reported at scientific meetings and summarized in published abstracts. However, abstracts are not subjected to peer review and do not include detailed methods and results needed to allow evaluation of conclusions that may be drawn.

Other information sources played a limited role. In a few cases I have supplemented my reliance on journal articles by reference to databases, technical reports, and articles in the popular (e.g. news articles) and semi-popular (trade magazine) media. This was only done to provide information on topics yet poorly covered in journal articles or to provide context and not as the primary basis for conclusions regarding actual or potential harm.

A separate expert report provided context regarding toxicological effects. The United States also engaged a toxicologist, Dr. Stanley D. Rice, to provide an expert report[6] on the toxicological effects of the oil released by the Macondo well blowout that I summarize briefly in Section 3 and refer to later in my report. Dr. Rice's report and the materials cited in it were helpful to me in providing a critical assessment of toxicological methods, concentrations at which effects may be elicited, and comparisons with the broader literature on oil effects. However, I independently reviewed the journal articles cited by Dr. Rice that reported results of studies addressing toxic effects of the Macondo well blowout and I drew my own conclusions.

The assessment did not involve analyses of extensive NRDA databases. Federal and state trustee agencies and BP are still conducting numerous studies through the Natural Resources Damage Assessment (NRDA) process under the Oil Pollution Act. Enormous quantities of raw data collected are available through online databases maintained by Federal agencies and BP,[7] but work products that contain analyses and interpretations of these data remain confidential and were not available to me. I reviewed the content and scope of the available NRDA databases and considered summaries produced by Dr. Rice, but I did not conduct my own analyses of the data contained in them for several reasons: (a) such primary analyses are best conducted by subject matter specialists (for example, organic chemists in the case of petroleum contaminants or ornithologists in the case of birds) who have the skills and experience needed for in-depth analysis and interpretation, (b) there are significant risks of misinterpretation without a full understanding of the methods and sampling context, particularly considering the limited time available for my assessment and (c) the NRD assessment is still ongoing.

A cautious approach was taken in drawing conclusions. Throughout the assessment I have used "actual harm" to describe a demonstrated effect that altered the normal functions and populations in an ecosystem. I used "potential harm" when evidence suggests that there might be

[6] Rice, S.D. (2014) Toxicological Impact of the MC252 Blowout, Oil Spill, and Response. Expert Report submitted on behalf of the United States. U.S. v. BP Exploration & Production et al.
[7] BP (2014) Gulf Science Data. http://gulfsciencedata.bp.com/, http://gulfsciencedata.bp.com/, http://www.gulfspillrestoration.noaa.gov/oil-spill/gulf-spill-data/

harm but does not unambiguously demonstrate it. In some cases, the available scientific literature allowed me to draw confident conclusions as to actual or potential harm. However, in many others definitive conclusions cannot yet be drawn, particularly considering that research is ongoing and that effects may be delayed. Thus, I have been cautious in my approach in not pre-judging harm except where it can be demonstrated or dismissed with a high level of certainty, particularly in the distinction between "actual" and "potential" harm.

3. HYDROCARBONS AND THEIR TOXICITY

Dr. Stanley Rice's expert report, "Toxicological Impact of the MC252 Blowout, Oil Spill, and Response,"[8] includes a primer on the chemistry of oil, chemical dispersants and their toxicity. It reviews how the paradigm of oil spill effects has evolved from learning during the study of earlier oil spills, particularly the Exxon Valdez spill in Alaska in 1989. And, it evaluates the potential for toxicity damage as a result of the Macondo well blowout based on available literature and data. Here, I will just touch on a few salient points in this report that set the stage for my assessment. I have independently reviewed Dr. Rice's cited materials related to the Macodo well blowout and concur with his summary of them.

Hydrocarbons released by the Macondo well blowout include literally thousands of compounds, ranging from light hydrocarbons containing one to four atoms of carbon that are gaseous under surface pressure and temperature conditions (methane, ethane, propane, and butane) to large molecules containing a score and more carbon atoms. Macondo well oil consisted mainly of alkanes (74% by mass), in which the carbon atoms are joined by a single bond. Aromatic hydrocarbons, which contain double-bonded carbon rings, comprised 16% by weight. Polycyclic aromatic hydrocarbons (PAHs, containing two or more rings) made up just approximately 3.9% by mass, but are of particular importance because they are known to be particularly toxic. Macondo well oil is similar to other crude oils in its PAH composition and poses similar toxic risks as, for example, the Alaska North Slope oil that spilled from the Exxon Valdez.

The hydrocarbon mixtures change as they are released into the environment as a result of differences in the solubility and volatility of different compounds as well as their susceptibility to degradation by microorganisms and sunlight. PAHs are more resistant to degradation and, thus, can persist in the environment as long-term contaminants and accumulate in lipid-rich tissues of organisms. A chemical dispersant injected where oil gushed from the wellhead or marine riser or sprayed onto surface oil slicks had little toxicity in itself, but increased the amount of oil dissolved or dispersed in the water column and thus the toxic exposure to aquatic organism.

Scientific understanding of the effects of oil in the marine environment has shifted the paradigm that earlier focused on obvious and lethal effects on birds and shoreline organisms to the realization that even very low concentrations of PAHs below the water's surface in dissolved or

[8] Rice, S.D. (2014) Toxicological Impact of the MC252 Blowout, Oil Spill, and Response. Expert Report submitted on behalf of the United States. U.S. v. BP Exploration & Production et al.

droplet form can have toxic effects on sensitive life stages of marine animals, such as the embryos and larvae of fish living in the plankton. Sublethal toxicity that does not directly kill the organism but impairs its development, diminishes its survival, or increases its susceptibility to predators may occur at PAH exposure concentrations in the low parts per billion range. Persistent contamination in sediments that are poorly oxygenated can result in a chronic source of toxic exposure. Also, acute effects on animal populations can have the ripple effect of longer-term recruitment failures, yielding surprising consequences that might not be evident until years later.

In the context of this more contemporary paradigm, Dr. Rice compared the results of a few careful experiments to determine the sublethal effects of Macondo well oil on sensitive fish embryos, larvae and juveniles to the concentrations of PAHs exceeding 0.5 parts per billion measured in surface waters during the period surface oil slicks were present. Based on all of the evidence and materials, he concluded that there were likely toxic effects on early life history stages in the water column over large areas and for extended periods during the summer of 2010.

4. SCALE OF HYDROCARBON CONTAMINATION

4.1. Location and Duration of the Release

Throughout this report I refer to the Macondo well blowout because the hydrocarbons were released from a deep-sea wellhead rather than spilled on the ocean surface by the *Deepwater Horizon* drilling rig. The Macondo wellhead, located in the Mississippi Canyon Area Lease Block 252, 41 miles (66 km) off the southeastern tip of Louisiana, was in approximately 5,000 feet (1,500 meters) of water. For 87 days the well released more oil and gas and from a greater depth than any oil pollution event in Unites States history until the flow was finally stanched on July 15, 2010.

The duration and location of the release of oil and gas have an influence on actual or potential harm. A release that, although voluminous, occurs over a short period of time, such as from a tanker spill, might have a more acute effect, but a substantial release over an extended period has the potential to harm organisms through repeated exposure or during critical phases of their life histories or their migration. In comparison to other notable offshore blowouts, releases from the Macondo blowout were of longer duration (87 days) than the 1969 blowout in Santa Barbara Channel, California (largely confined to two weeks), but shorter duration than the 1979 blowout at the *Ixtoc I* platform off Yucatan (nine months). I refer to these two examples here and in later comparisons rather than oil spills from ships or land-based facilities, as they were also blowouts emanating from the seabed and continuing over an extended period.

4.2. Amount and Composition of Oil and Gas Released

The amount of oil released into the environment was the subject of litigation in Phase Two of this trial. The United States presented evidence that approximately 5 million barrels of oil exited the Macondo well of which approximately 812,000 barrels were collected by the Top Hat containment device, the capping stack and the drilling vessel *Helix Q4000*. This left 4.2 million barrels of oil that

were released into the Gulf of Mexico where the oil could result in harm to the ecosystems and resources. It is not my objective to present an independent opinion on the volume of oil released, but to: (a) set a comparative context; (b) consider the implications of the rate of flow; (c) indicate that large amounts of hydrocarbons in addition to what were considered to be oil were also released; and (d) present a background for consideration of the fate of these various hydrocarbons, including those compounds that at standard temperature and pressure exist in a gaseous form.

The rate of oil release was unprecedented. By any estimate, the Macondo well blowout resulted in the release of more oil to the marine environment than any previous incident in the United States, resulting in a concomitantly great potential for environmental harm. The rates at which liquid hydrocarbons flowed from the Macondo well as determined by the United States Phase Two experts varied from approximately 63,000 to 53,000 barrels per day,[9] progressively declining until the well was capped.[10] This is significantly greater that the flow rates from the *Ixtoc I* (20,000 to 30,000 barrels per day) or Santa Barbara Channel (less than 10,000) per day. Even the single-phase separation estimates oil volume by BP's Phase Two expert are greater than the flow rates from *Ixtoc I*.[11] Flow rate is of major consequence to the fate and effects of released oil. The numerous natural oil seeps in the Gulf of Mexico collectively release between 1,500 and 3,800 barrels per day according to the National Research Council.[12] The flow rate of an individual seep is of the order of 10 barrels per day, thousands of times less than the discharge rate of the Macondo well by any estimate. This limits the extent of a natural seep's impacts and any surface oil slicks form thin surface sheens so spatially limited that they can be used to pinpoint the location of seeps.[13]

Traditional methods to characterize oil can account for only one half of the material that flowed from the Macondo well. In addition to the "liquid" oil released during the spill, gaseous hydrocarbons also posed potential harm to Gulf ecosystems. Experts in the Phase Two trial presented evidence that for every stock tank barrel of oil discharged, over 2,000 standard cubic feet of gas at STP were also discharged.[14] For reference, that is about the volume of a 40-foot long cargo container of gas for every barrel of oil. Eighty-eight percent of this gas was methane and the oil contained 74% saturated hydrocarbons, 16% aromatic hydrocarbons and 10% polar hydrocarbons, with no evidence of sub-seafloor biodegradation.[15] The polar molecules contain oxygen, nitrogen and sulfur have positive and negative charges on either end; many of these compounds are

[9] United States' Proposed Findings of Fact for Quantification Segment of the Phase Two Trial (Rec. Doc 12048-1) 63, 65.
[10] McNutt MK, Camilli R, Crone TJ, Guthrie GD, Hsieh PA, Ryerson TB, Savas O, Shaffer F (2012) Review of flow rate estimates of the Deepwater Horizon oil spill. Proc Natl Acad Sci USA 109:20260-20267
[11] C. Whitson (2013) Expert Rebuttal Report prepared on behalf of BP (TREX-011496). U.S. v. BP Exploration & Production et al.
[12] National Research Council (2013) An Ecosystem Services Approach to Assessing the Impacts of the Deepwater Horizon Oil Spill in the Gulf of Mexico. National Academy Press, Washington D.C.
[13] Hu C, Li X, Pichel WG, Muller-Karger FE (2009) Detection of natural oil slicks in the NW Gulf of Mexico using MODIS imagery. Geophys Res Lett 36:L01604
[14] Zick, A. (2013) Expert Rebuttal Report prepared on behalf of the United States (TREX-011491). U.S. v. BP Exploration & Production et al. 14, 20
[15] Reddy CM, Arey JS, Seewald JS, Sylva SP, Lemkau KL, Nelson RK, Carmichael CA, McIntyre CP, Fenwick J, Ventura GT, Van Mooy BAS, Camilli R (2012) Composition and fate of gas and oil released to the water column during the Deepwater Horizon oil spill. Proc Natl Acad Sci USA 109:20229-20234

resistant to evaporation and bio- or photodegradation and have the potential to remain in the environment for a long time. Their longevity increases the potential for these compounds to cause long-term environmental harm.

4.3. Three-Dimensional Scope of the Blowout

Assessment of the blowout requires a different perspective than for a traditional oil spill. The depth of the Macondo well blowout, 5,000 feet below the ocean surface, resulted in effects on a broader range of ecosystems and organisms than a more "traditional" oil spill may have. In comparison, the Macondo well blowout occurred at a much greater depth than either the Santa Barbara Channel (188 feet) or *Ixtoc I* (160 feet) blowouts. The largest and deepest blowout, the Macondo well blowout has substantially changed scientists' concepts of fate of hydrocarbons released (Figure 2). Deeper waters are isolated from the surface waters because the former are colder, denser and too deep to be mixed by winds and seasonal temperature changes occurring at the surface. Consequently, substantial portions of the hydrocarbons were either dissolved or not buoyant enough to ascend to the surface of the ocean and thus were retained in the deep layers of the Gulf. This was a central issue during Phase Two of this trial concerning the volume of oil to be considered in the violation: was it the amount released from the well at the bottom of the ocean or the amount reaching its surface?

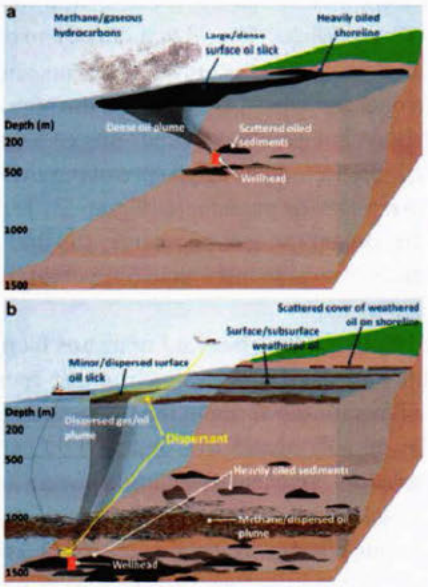

Figure 2. Traditional view of the fate of hydrocarbon released from a blowout (a) compared to the emerging model of a deepwater blowout (b).

While traditionally the focus in oil spill control and assessment is on floating oil and its impacts on shorelines and animals that live at the surface, one needs in this case to place greater than normal consideration of the impacts on the organisms living in the deep waters of the Gulf and on the seabed.

Hydrocarbon-rich plumes extended from the Macondo wellhead. The subsurface plumes emanating from the Macondo wellhead consisted of dissolved hydrocarbons and tiny droplets of oil dispersed by the turbulent forces acting on the oil and gas mixture as it exited the well with great force. Dr. Rice pointed out that both dissolved components and droplets exposed organisms to toxic effects. While larger droplets of oil rose to the surface, the fine droplets and dissolved hydrocarbons remained within the layer of seawater in which they were dispersed (approximately

1,100 to 1,300 meters below the sea surface, centered at about 1,175 meters).[16] Much like smoke coming from a smokestack, the subsurface plumes of hydrocarbons spread and became more diffuse with distance from the source as the oil mixed with the surrounding seawater. The direction in which the plume drifted depended on the direction of the prevailing current flow. This was mainly to the southwest along the continental slope, but occasionally in other directions. The deepwater plume was detectable as far as 300 nautical miles from the Macondo wellhead.[17] In addition to the deepwater plume, subsurface plumes were identified with mid-depths of 25, 265 and 865 meters depth.[18]

Surface oil slicks extended over a vast area during the summer of 2010. The potential environmental impact of the Macondo well blowout was exacerbated by the vast area covered by surface oil slicks. The oil that did rise to the surface of the Gulf of Mexico formed into slicks that were moved about by surface currents and winds that varied over time. Initially, prevailing currents and winds, and perhaps the Mississippi River freshwater discharge plume, kept oil slicks offshore, but eventually winds played a major role in pushing the oil toward the coasts along the northern Gulf. Floating oil spread out over the continental shelf from southeastern Louisiana to the western Florida panhandle (Figure 3). From the time of the Macondo well blowout through August 2010, 180,000 square kilometers (68,000 square miles) of sea surface had floating oil at one time or another,[19] an area more than 50% greater than the land area of the state of Louisiana.

Oil impacted beaches and marshes from Florida to Texas. Floating oil first began to come ashore by May 19, 2010, and in a peer-reviewed article published by technical contractors working on oil response[20] for both the U.S. government and BP, it was estimated that Macondo well blowout oil eventually stranded on at least 1,773 kilometers (1,102 miles) of shoreline in Louisiana, Mississippi, Alabama and Florida during 2010.[21] Trace oiling was also found along 58 kilometers (36 miles) of the Texas coast during less frequent surveys there, bringing the total length of shoreline affected by visible oil[22] to at least 1,881 kilometers (1,138 miles), a distance exceeding the road mileage from New Orleans to Washington, DC. The extent of shoreline oiling reported in this

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[16] Spier C, Stringfellow WT, Hazen TC, Conrad M (2013) Distribution of hydrocarbons released during the 2010 MC252 oil spill in deep offshore waters. Environmental Pollution 173:224-230

[17] Kessler JD, Valentine DL, Redmond MC, Du M, Chan EW, Mendes SD, Quiroz EW, Villanueva CJ, Shusta SS, Werra LM, Yvon-Lewis SA, Weber TC (2011) A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. Science 331:312-315

[18] Spier C, Stringfellow WT, Hazen TC, Conrad M (2013) Distribution of hydrocarbons released during the 2010 MC252 oil spill in deep offshore waters. Environmental Pollution 173:224-230

[19] SkyTruth (2010, July 27) BP/Gulf Oil Spill—68,000 Square Miles of Direct Impact. http://blog.skytruth.org/2010/07/bp-gulf-oil-spill-68000-square-miles-of.html

[21] Michel J, Owens EH, Zengel S, Graham A, Nixon Z, Allard T, Holton W, Reimer PD, Lamarche A, White M, Rutherford N, Childs C, Mauseth G, Challenger G, Taylor E (2013) Extent and degree of shoreline oiling: Deepwater Horizon oil spill, Gulf of Mexico, USA. PLoS One 8:e65087

[22] Based on deposition testimony of Dr. Jacqui Michel, the Shoreline Clean-up Assessment Team calculated these numbers measuring visible oil only (Michel Dep. 93:16-21; 294:1-8); areas where oil could not be seen by the SCAT field team were categorized as no observable oil. *Id.* at 292:9-20. Therefore, the SCAT did not include any rubric for identifying areas of shoreline impacted by naturally dissipated Macondo oil or its constituents. *Id.* at 112:19-113:12; 114:23-115:15. The SCAT did not perform any water sampling to assess where along the Gulf coast Macondo oil may have been present but was not visible. *Id.* at 291:1-10. NRDA analysis of the extent of shoreline oiling is ongoing. *Id.* at 197:5-198:16.

study used data collected for shoreline clean-up assessment and should be regarded as a smoothed estimate of shoreline impacted. If every nook and cranny that had oil were to be individually measured, estimates of the length of impacted shoreline would have been larger.

Figure 3. Duration for which floating oil was observed during 2010 (Baron 2012 after ERMA).

The shoreline impacts of the *Ixtoc I* and Santa Barbara Channel blowouts were estimated to extend over 261 and 56 kilometers, respectively. In the history of documented oil spills, only the *Exxon Valdez* spill oiled more a greater length of shoreline (2,100 kilometers) as it was transported alongshore by the Alaska Coastal Current. Based on the oil spill response surveys, of the shorelines oiled by the Macondo well blowout, approximately 51% were beaches (mainly in Louisiana, Alabama and Florida), 45% marshes (virtually all in Louisiana), and about 4% other shoreline types. Of the 1,773 km of shoreline ever observed by response workers as having been oiled in 2010 (excluding Texas), approximately 48% still had some degree of oiling after one year and 39% remained with some oil after two years. Oil mixed with sand in the form of residue balls, patties and mats and oiled marshes remained in limited areas into 2014.[23]

4.4. Control Measures and Their Consequences

In addition to the steps taken to contain the Macondo well blowout by capping the well or collecting oil at the wellhead, various measures were undertaken to control the hydrocarbons after they were released into the environment. They included measures taken to:

(a) reduce the amount of oil reaching the surface through application of chemical dispersants at the wellhead;

[23] Blair K (2014) 1,783 pounds of BP oil removed from seashore. Pensacola News Journal, http://on.pnj.com/1rDYXFx Gannett, Pensacola, FL

(b) reduce the oil at the ocean surface, including skimming and removal, burning, and surface application of dispersants;

(c) block oil from reaching coastal areas, including deployment of barriers such as booms and barges, construction of sand berms, and opening of river diversions to keep oil from moving up estuaries; and

(d) remove oil from shorelines through scraping or excavation.

While each of the control measures was taken to reduce certain impacts, each also had at least the potential to result in other environmental harm.[24] For example, the decision to allow application of dispersants at the wellhead was based on weighing the benefits of reducing the amount of oil that would reach the surface, and potentially be transported to sensitive coastal areas or contact birds or marine mammals, against the risks of harm that might be caused by introducing toxic compounds into the waters of the Gulf of Mexico. The effects of control measures must be taken into account in assessing real or potential harm from the Macondo well blowout. Decisions on the use of such measures represented tradeoffs among choices, each of which could result in different potential harms, tradeoffs that would not have had to be confronted but for the Macondo well blowout.

4.5. Fate of Hydrocarbons Released to the Environment

A comprehensive, quantitative analysis of the long-term fate of the hydrocarbons released from the Macondo well blowout is beyond the scope of this report. Rather, the discussion here focuses on how the component hydrocarbons have very different fates and how this affects the nature of real or potential harm to Gulf organisms, ecosystems and resources.

In some cases oil and water actually do mix. Everyone thinks that oil and water generally do not mix. In reality, the mixing of Macondo well oil with Gulf waters increased toxic exposure. Research into Macondo oil clearly demonstrates that a substantial portion of the hydrocarbons released was retained in the deep waters of the Gulf, particularly the hydrocarbons of low molecular weight. Essentially all of the methane and the other hydrocarbons that are gaseous at standard temperature and pressure dissolved in the deep ocean before they could rise to the surface and thus did not reach the atmosphere.[25] Approximately 69% of the mass of leaked hydrocarbons that was retained in the deep plume consisted of readily soluble hydrocarbons, including the gaseous hydrocarbons and lighter aromatic hydrocarbons, such as benzene, and 31% consisted of very small-sized oil

[24] Peterson CH, Anderson SS, Cherr GN, Ambrose RF, Anghera S, Bay S, Blum M, Condon R, Dean TA, Graham M, Guzy M, Hampton S, Joye S, Lambrinos J, Mate B, Meffert D, Powers SP, Somasundaran P, Spies RB, Taylor CM, Tjeerdema R, Adams EE (2012) A tale of two spills: Novel science and policy implications of an emerging new oil spill model. BioScience 62:461-469

[25] Yvon-Lewis SA, Hu L, Kessler J (2011) Methane flux to the atmosphere from the Deepwater Horizon oil disaster. Geophys Res Lett 38:L01602

droplets trapped in subsurface layers.[26] These small droplets of oil were emulsified in water, like a well-mixed salad dressing. As indicated in Dr. Rice's expert report the dissolution of lighter aromatic hydrocarbons emanating from a deep well blowout is noteworthy as it provides a mechanism for these compounds to reach potentially toxic concentrations in seawater.[27] In a conventional surface spill, these aromatic compounds would be predominantly lost to evaporation into the atmosphere and not much would mix into seawater.

But some oil floats, evaporates and degrades. The Macondo well oil that did reach surface waters formed extensive slicks that posed risks to organisms at or near the Gulf surface. Buoyant oil that rose above the deepwater plume reached the surface of the Gulf within about 3-10 hours within about a 2 square kilometer area down-current of the well. During the ascent significant amounts of lighter aromatic and other relatively soluble hydrocarbons dissolved into subsurface waters. An estimated 14% of the hydrocarbons reaching the Gulf surface were susceptible to evaporation into the atmosphere. The remaining weathered oil in surface slicks was depleted in hydrocarbons containing 14 and fewer carbon atoms through dissolution and evaporation. However, PAHs and some portion of the soluble or volatile compounds remained in the slicks, replenished over 87 days with fresher oil rising from the wellhead. Biodegradation, photo-oxidation, burning and application of chemical dispersants further altered the composition of oil slicks. For example, heavier PAHs and alkanes were more resistant to photodegradation.[28] Emulsions of water in oil (like mayonnaise) typically formed, making the mass thicker, resistant to further degradation and very sticky on contact.

5. OFFSHORE ECOSYSTEMS

5.1. The Deep-Sea Plume

The deep-sea hydrocarbon plume placed organisms living at those depths or on the seabed at significant risk. A deep-sea plume, enriched in dissolved gaseous and other soluble hydrocarbons and fine droplets of oil extended from the wellhead between 1,100 and 1,300 meters below the surface in the direction of the prevailing current flow. Current flows at these depths were generally slow (0.1-0.2 meters per second),[29] thus constraining the mixing with surrounding seawater and, thus, the dilution of the plume.

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[26] Ryerson TB, Camilli R, Kessler JD, Kujawinski EB, Reddy CM, Valentine DL, Atlas E, Blake DR, de Gouw J, Meinardi S, Parrish DD, Peischl J, Seewald JS, Warneke C (2012) Chemical data quantify Deepwater Horizon hydrocarbon flow rate and environmental distribution. Proc Natl Acad Sci USA 109:20246-20253

[27] Rice, S.D. (2014) Toxicological Impact of the MC252 Blowout, Oil Spill, and Response. Expert Report submitted on behalf of the United States. U.S. v. BP Exploration & Production et al., 18-19.

[28] King SM, Leaf PA, Olson AC, Ray PZ, Tarr MA (2014) Photolytic and photocatalytic degradation of surface oil from the Deepwater Horizon spill. Chemosphere 95:415-422

[29] Lindo-Atichati D, Paris CB, Le Hénaff M, Schedler M, Valladares Juárez AG, Müller R (2014) Simulating the effects of droplet size, high-pressure biodegradation, and variable flow rate on the subsea evolution of deep plumes from the Macondo blowout. Deep-Sea Res II http://dx.doi.org/10.1016/j.dsr2.2014.01.011

Dispersant application intensified rather than caused the deep-sea plume. The deep-sea plume would have formed even if the chemical dispersant Corexit 9500 had not been injected into the gushing hydrocarbons. The dispersant had no real effect on the gaseous hydrocarbons and the turbulent mixing as the gas and oil exited the crumpled marine riser or wellhead with great force facilitated dissolution and fine droplet formation of liquid hydrocarbons. The degree to which the injection of the dispersant increased the retention of oil in the deepwater plume and prevented it from reaching the surface of the Gulf has been actively debated. One modeling study suggested that the injection of the dispersant only marginally decreased the amount of oil surfacing.[30] However, observations of the rate at which oil was surfacing when the dispersant was applied compared to when it was not indicate that the injection of dispersant reduced but did not eliminate surfacing oil, with the consequence that dispersant application resulted in the retention of more oil in the deep-sea plume.[31]

Significant amounts of hydrocarbons dissolved in the deep-sea plume resulting in exposure levels toxic to marine organisms. At the pressure and temperature existing at 1,500 meters, the discharging methane had a tendency to form methane hydrate crystals. This is the phenomenon that limited the effectiveness of the funnel-like "cofferdam" initially deployed to capture the oil exiting the well—it quickly became clogged by the ice-like hydrates.[32] The methane eventually dissolved in the seawater, along with the other gaseous hydrocarbons. Concentrations of methane measured in the plume were as high as 3 parts per million (180 micromoles per liter), tens of thousands of times higher than background levels.[33] Dissolved concentrations of mono-aromatic hydrocarbons (relatively soluble benzene, toluene, ethylbenzene, and xylenes) were measured in excess of 50 parts per billion.[34] PAH concentrations as high as 189 parts per billion were also measured.[35] Dr. Rice reported that publically available NRDA data indicate that some samples collected in the plume extending over 500 kilometers in a northeast-to-southwest direction exceeded 0.5 parts per billion.[36] Based on this evidence of exposure he concluded that toxicity damage was likely. To my knowledge no results from research on the effects of the plume hydrocarbons on planktonic and swimming organisms living at the depths of the deep-sea plume

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[30] Paris CB, Henaff ML, Aman ZM, Subramaniam A, Helgers J, Wang DP, Kourafalou VH, Srinivasan A (2012) Evolution of the Macondo well blowout: simulating the effects of the circulation and synthetic dispersants on the subsea oil transport. Environ Sci Technol 46:13293-13302

[31] Ryerson TB, Camilli R, Kessler JD, Kujawinski EB, Reddy CM, Valentine DL, Atlas E, Blake DR, de Gouw J, Meinardi S, Parrish DD, Peischl J, Seewald JS, Warneke C (2012) Chemical data quantify Deepwater Horizon hydrocarbon flow rate and environmental distribution. Proc Natl Acad Sci USA 109:20246-20253

[32] National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011) DEEP WATER The Gulf Oil Disaster and the Future of Offshore Drilling U.S. Government Printing Office, Washington D.C.

[33] Crespo-Medina M, Meile CD, Hunter KS, Diercks AR, Asper VL, Orphan VJ, Tavormina PL, Nigro LM, Battles JJ, Chanton JP, Shiller AM, Joung DJ, Amon RMW, Bracco A, Montoya JP, Villareal TA, Wood AM, Joye SB (2014) The rise and fall of methanotrophy following a deepwater oil-well blowout. Nature Geosci 7:423-427

[34] 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

[35] Diercks A-R, Highsmith RC, Asper VL, Joung DJ, Xhou Z, Guo L, Shiller AM, Joye SB, Teske, AP, Guinasso N, Wade TL, Lohrenz SE (2010) Characterization of subsurface polycyclic aromatic hydrocarbons at the Deepwater Horizon site. Geophys Res Lett 37:L20602

[36] Rice, S.D. (2014) Toxicological Impact of the MC252 Blowout, Oil Spill, and Response. Expert Report submitted on behalf of the United States. U.S. v. BP Exploration & Production et al.

have been published, however there was at least potential harm to this component of the ecosystem.

Blooms of bacteria grew on the dissolved and suspended hydrocarbons providing a mechanism for deposition of hydrocarbons and other organic matter on the seafloor. Populations of bacteria, normally at low levels at this depth in the water column, grew explosively on the lighter hydrocarbons in the deepwater plume. New techniques in molecular genetics were employed to show that types of bacteria capable of metabolizing propane and ethane grew rapidly within days, priming the degradation of other hydrocarbons by other types of bacteria in the aging plume.[37] Bacteria specializing in methane oxidation then became more prevalent[38] with oxidation rates peaking in June and declining through August available methane was depleted. Degradation of higher molecular weight hydrocarbons proceeded at much slower rates.[39] The telltale indicator of biodegradation of hydrocarbons in the deep-sea plume was the occurrence of anomalously low levels of dissolved oxygen at the depths of the plume detectable as far as 300 nautical miles from the Macondo well.[40]

As bacteria populations grew and died they exuded organic polysaccharides, much like mucous. Aggregates of such organic material with entrained microbes and mineral particles are common in the ocean and are commonly referred to as "marine snow." It is very likely that hydrocarbons and oil-dispersant mixtures in the deep-sea plume stimulated a tremendous production of marine snow through a process similar to that observed in surface waters of the Gulf below oil slicks.[41] Similarly, much of this marine snow produced from the bacterial blooms in the deep-sea plume and in lesser plumes at intermediate depths sank to the seafloor together with bacterial biomass and entrained suspended sediments and oil droplets in what has been called a "dirty blizzard"[42] or more formally Marine Oil Snow Sedimentation and Flocculent Accumulation. The harm to benthic, or bottom dwelling, organisms resulting from this hydrocarbon-stimulated biodeposition is discussed in Section 4.4. But the salient point is that while microbial biodegradation removed hydrocarbons from the water column, it also resulted in the deposition of components of petroleum on the seabed

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[37] Valentine DL, Kessler JD, Redmond MC, Mendes SD, Heintz MB, Farwell C, Hu L, Kinnaman FS, Yvon-Lewis S, Du M, Chan EW, Garcia Tigreros F, Villanueva CJ (2010) Propane respiration jump-starts microbial response to a deep oil spill. Science 330:208-211

[38] Kessler JD, Valentine DL, Redmond MC, Du M, Chan EW, Mendes SD, Quiroz EW, Villanueva CJ, Shusta SS, Werra LM, Yvon-Lewis SA, Weber TC (2011) A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. Science 331:312-315

[39] Mason O, Han J, Woyke T, Jansson J (2014) Single-cell genomics reveals features of a *Colwellia* species that was dominant during the Deepwater Horizon oil spill. Front Microbiol 5

[40] Kessler JD, Valentine DL, Redmond MC, Du M, Chan EW, Mendes SD, Quiroz EW, Villanueva CJ, Shusta SS, Werra LM, Yvon-Lewis SA, Weber TC (2011) A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. Science 331:312-315

[41] Passow U, Ziervogel K, Asper V, Diercks A (2012) Marine snow formation in the aftermath of the Deepwater Horizon oil spill in the Gulf of Mexico. Env Res Lett 7:035301

[42] Schrope M (2013) Dirty blizzard buried Deepwater Horizon oil. Nature 10.1038/nature.2013.12304

where they were less subject to dilution and more resistant to further degradation because of oxygen limitation.[43]

5.2. Surface Waters

The waters within 150 meters of the surface of the Gulf of Mexico are particularly biologically important as this is where there is sufficient light to support photosynthetic production of organic material by phytoplankton (microscopic plants) and floating seaweeds (particularly *Sargassum*). The oceanic fish that we treasure—the tuna, mahi-mahi, mackerel, marlin and swordfish—live there and air breathing animals, including seabirds, sea turtles, and whales and dolphins, depend on these near-surface waters. Unlike the deep waters just discussed, surface waters are mixed by the winds, warm and cool seasonally, have oxygen supplied internally by plant photosynthesis, and are often depleted in mineral nutrients that limit both plant production and microbial oil degradation. The organisms living in near-surface waters were obviously also exposed to floating oil from the Macondo well blowout.

The important floating seaweed community was directly harmed. A particular ecological characteristic of the offshore waters of the northern Gulf of Mexico is the occurrence of floating brown algae of the genus *Sargassum*. These are the same algae that characteristically occur in floating masses and give the name Sargasso Sea to the central part of the North Atlantic Ocean east of the Gulf Stream. The northern Gulf of Mexico contains the next most productive *Sargassum* ecosystem. The algae lead a totally floating existence, kept at the sea surface by gas filled bladders, and attract a unique community of small animals that take advantage of the algae for the habitat structure it provides. *Sargassum* also provides important habitat for juvenile sea turtles[44] and fish (Figure 4).

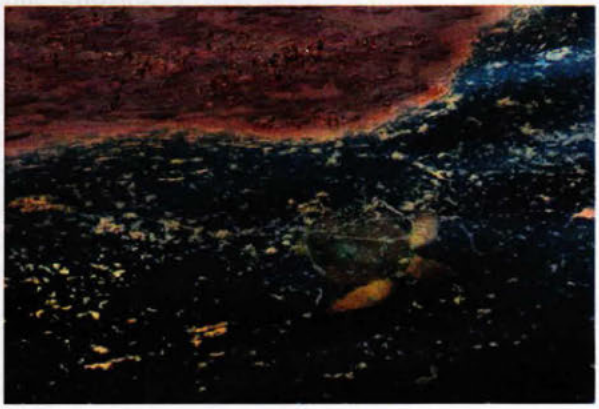

Figure 4. A sea turtle swims under a raft of *Sargassum* entrained in oil.

As oil slicks from the Macondo well blowout spread onto the continental shelf between the Chandeleur Islands and the Florida Panhandle during June 2010, scientists observed reductions in

[43] Mason OU, Scott NM, Gonzalez A, Robbins-Pianka A, Balum J, Kimbrel J, Bouskill NJ, Prestat E, Borglin S, Joyner DC, Fortney JL, Jurelevicius D, Stringfellow WT, Alvarez-Cohen L, Hazen TC, Knight R, Gilbert JA, Jansson JK (2014) Metagenomics reveals sediment microbial community response to Deepwater Horizon oil spill. ISME J 8:1464-1475

[44] Witherington B, Hirama S, Hardy R (2012) Young sea turtles of the pelagic Sargassum-dominated drift community: habitat use, population density, and threats. Mar Ecol Prog Ser 463:1-22

the abundance of *Sargassum* at the surface.[45] Experiments were conducted that demonstrated that exposure to oil and, particularly, to chemically dispersed oil caused *Sargassum* to sink, a trend particularly pronounced for one of the two species, *Sargassum natans*. Dissolved oxygen levels around the *Sargassum* also dropped, more so when the oil was chemically dispersed. In addition to any toxic effects, sinking of an important habitat and stress induced by lowered dissolved oxygen likely resulted in actual harm to the plants and animals associated with floating *Sargassum* that came into contact with floating oil. While the harm to populations of animals associated with *Sargassum* was not directly measured, the investigators conducted simple calculations to demonstrate that the effects on sea turtle hatchings and juveniles could contribute to year-class failure. Follow-up aerial surveys in 2011 and 2012 documented a four-fold increase in *Sargassum* abundance over 2010 levels, suggesting that while the impact of the Macondo well blowout on this important habitat was particularly acute, it might not have been long-lasting.

Sea turtles suffered substantial mortalities and unusually high rates of stranding that have continued through at least 2013. Five species of sea turtles occur in the northern Gulf of Mexico: the green, hawksbill, Kemp's ridley, leatherback, and loggerhead. All are listed as endangered under the Endangered Species Act. Over one thousand sea turtles were collected in the Deepwater Horizon Response (see Table 2). Many of these were one to two year old turtles collected from the zone where their preferred *Sargassum* habitat and oil slicks converged. These turtles were fouled with sticky oil and had often ingested oil. Monthly turtle collections far exceeded historical records of turtle strandings (washed ashore or found floating dead or in a weakened condition) during the period in which there was abundant floating oil (Figure 5).

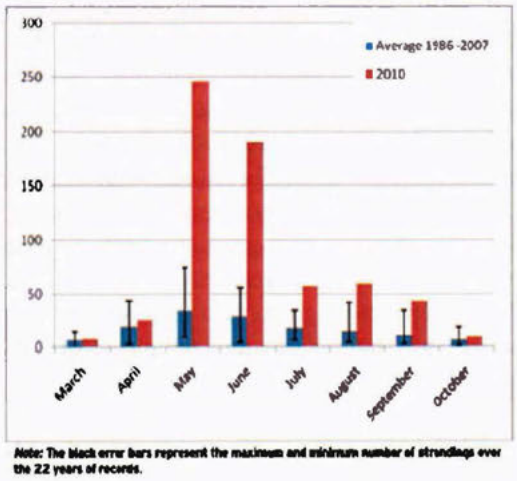

Figure 5. Monthly sea turtle strandings in 2010 compared to long-term averages (compiled by Doug Inkley of the National Wildlife Federation using Sea Turtle Stranding and Salvage Network data).

In 2011-2013 approximately 500 turtle strandings per year were observed from Alabama to the upper Texas coast (Table 1), a five-fold increase above the historical rate.[46] Possible reasons for the increased strandings under investigation include fishing activities that result in bycatch, biotoxins from harmful algal blooms, and impacts from the Macondo well blowout.

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[45] Powers SP, Hernandez FJ, Condon RH, Drymon JM, Free CM (2013) Novel pathways for injury from offshore oil spills: direct, sublethal and indirect effects of the Deepwater Horizon oil spill on pelagic Sargassum communities. PLoS One 8:e74802.

[46] National Marine Fisheries Service (2013) Sea Turtle Strandings in the Gulf of Mexico NOAA Fisheries Office of Protected Resources, 2014, http://www.nmfs.noaa.gov/pr/species/turtles/gulfofmexico.htm

Table 1. Sea turtle strandings in the Gulf of Mexico for the years 2011-2013 by species and state (Source: National Marine Fisheries Service)

	2011			2012				2013			
	AL	MS	LA	AL	MS	LA	TX	AL	MS	LA	TX
Loggerhead	10	4	19	4	3	3	15	6	11	6	19
Green	4	4	4	3	1	9	34	3	2	4	19
Leatherback				1			2	2	1	1	
Hawksbill	4						1				2
Kemp's ridley	66	265	104	52	153	100	60	29	176	145	66
Unidentified	14	7	19	5	5	15	0	4	6	42	1
Total	98	280	146	65	162	127	112	44	196	198	107

Surface waters were contaminated by petroleum hydrocarbons emanating from surface oil slicks. Soluble hydrocarbons that did not go into solution on the way to the surface can dissolve into surface waters underneath oil slicks. Also, waves can break up and mix floating oil into the water column, further exposing marine organisms. Dr. Rice found that over half of the water samples taken in May 2010 within 50 meters of the surface had detectable contamination with petroleum hydrocarbons based on NRDA publically available data.[47] PAH concentrations in excess of 0.5 parts per billion were found in about half of the oil-contaminated samples in May. As the oil slicks spread and sampling broadened the percentage of water samples with detectable oil decreased but the footprint of demonstrated contamination broadened. By July stations yielding PAH concentrations greater than 0.5 parts per billion—concentrations that can be harmful to sensitive life states of fish, for example—were spread over a geographic region covering 100,000 square kilometers.

Animal plankton collected from near-surface waters of the deep Gulf of Mexico where floating oil was prevalent showed evidence of exposure to Macondo well oil.[48] Their tissues contained higher concentrations and characteristics of PAHs indicative of a liquid fossil fuel source.

Application of chemical dispersants to oil slicks increased incorporation of Macondo well oil into surface waters. The reincorporation of floating oil into the water column was purposefully enhanced by the application of the dispersants sprayed onto slicks from aircraft or vessels for reasons of operational safety and to reduce the amount of floating oil that could come ashore (Section 3.4). A total of one million gallons of dispersants was applied to surface oil slicks, initially both Corexit 9527 and Corexit 9500 and later only Corexit 9500. The large majority of these applications were within 30 nautical miles (55 kilometers) of the Macondo well, mostly onto waters overlying the deep Gulf of Mexico or the deeper parts of the continental shelf (Figure 8). Field

[47] Rice, S.D. (2014) Toxicological Impact of the MC252 Blowout, Oil Spill, and Response. Expert Report submitted on behalf of the United States. U.S. v. BP Exploration & Production et al., 21-22.
[48] Mitra S, Kimmel DG, Snyder J, Scalise K, McGlaughon BD, Roman MR, Jahn GL, Pierson JJ, Brandt SB, Montoya JP, Rosenbauer RJ, Lorenson TD, Wong FL, Campbell PL (2012) Macondo-1 well oil-derived polycyclic aromatic hydrocarbons in mesozooplankton from the northern Gulf of Mexico. Geophys Res Lett 39:L01605

studies demonstrated that when surface application of dispersant was effective in breaking up slicks, there was greater incorporation of total petroleum hydrocarbons (TPH) and total polycyclic aromatic hydrocarbons (TPAH) within the top 5 meters of the water column.[49]

Because dispersants are chemicals added to the environment, their use in controlling oil released from the Macondo well blowout engendered concerns among some scientists as well as the broader public about their toxic effects on humans as well as marine life. Experimental results have repeatedly shown that mixtures of oil and dispersants in seawater are more toxic than that of those with oil alone or dispersants alone.[50] The toxic effect results primarily from dispersants increasing the concentrations of toxic oil compounds in solution, rather than increasing the inherent toxicity of the constituent compounds of dispersants themselves.

Figure 6. Over 90% of the aerial sorties applied dispersants within the gray area around the Macondo well. Applications within 3 miles of the open coast were prohibited.

Furthermore, as the vast majority of surface applications of dispersants occurred over the continental slope and outer continental shelf well away from shore (Figure 6), the concentrations of dispersants to which inner shelf and coastal organisms were exposed were relatively low. While some of the applied dispersant could have been entrained in the oil and moved ashore by wind and currents it would have been subject to considerable dilution and degradation before reaching the inner continental shelf or coastal environments. Nonetheless, traces of the principal surfactant component of Corexit, dioctyl sodium sulfosuccinate, were found in tar balls and sand patties collected from beaches as long as four years after the Macondo well blowout.[51] However, these were at very low concentrations of not more than 0.0012% of amount of oil contained in these residues and mostly ten to one-hundred times lower.

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[49] Bejarano AC, Levine E, Mearns AJ (2013) Effectiveness and potential ecological effects of offshore surface dispersant use during the Deepwater Horizon oil spill: a retrospective analysis of monitoring data. Environ Monit Assess 185:10281-10295

[50] 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. Environ Toxicol Chem 30:2244-2252. These results are also summarized by Dr. Rice at 21-22.

[51] White HK, Lyons SL, Harrison SJ, Findley DM, Liu Y, Kujawinski EB (2014) Long-term persistence of dispersants following the Deepwater Horizon oil spill. Environ Sci Technol Lett 1:295-299

Oil harmed planktonic organisms and affected their food webs. There is convincing evidence that petroleum hydrocarbons, very likely from the Macondo well blowout, entered the planktonic food webs on the inner continental shelf off Alabama. This is based on evidence derived from analysis of stable carbon isotopes[52] and the radioisotope carbon-14.[53] In nature carbon-13 is rare (about 1% of the carbon) compared to carbon-12, but is stable and does not decay into another isotope. As a result small differences in the ratios of these isotopes can be used as a tracer of the original sources of organic matter within a food chain. Marine phytoplankton, marsh grasses, trees or fossil hydrocarbons have distinctive signatures. Carbon-14, on the other hand, is radioactive and decays at a fixed rate over time into nitrogen-14. Fossil hydrocarbons, being very old, contain essentially no carbon-14. The organic carbon contained in bacteria that have been growing on fossil oil or gas contains little carbon-14 and has a ratio of carbon-13 to carbon-12 more like oil than marine phytoplankton. This would also hold true also for those small planktonic organisms that fed on those bacteria. As Macondo oil slicks moved across the continental shelf off Alabama during June and July of 2010, the ratio of carbon isotopes in small suspended particles (including bacteria) and in small planktonic animals shifted in a direction of more oil entering the food web, before returning to baseline levels later that year.

Experiments conducted in Alabama, however, indicated that, while chemically dispersed oil was assimilated by bacteria, dispersant-oil mixtures suppressed populations of planktonic protozoans, know as ciliates, that consume the bacteria.[54] Other experiments conducted on the continental shelf off Louisiana and Texas demonstrated that small, planktonic crustaceans (copepods) accumulated PAHs when exposed to oil in water and suffered acute mortality at concentration of 32 parts per billion.[55] Chemically dispersed oil was two to three times more toxic than oil alone. For reasons not understood, the presence of another type of protozoan (a species of dinoflagellate) reduced the harmful effects on the small crustaceans and the transfer of PAHs up the food chain. Various species of gelatinous plankton (jellyfish and comb jellies) and their larval stages were also shown experimentally to accumulate PAHs from oil contaminated Gulf waters and to suffer mortality at 150 parts per billion total hydrocarbons (probably representing effective PAH concentrations as low as 1.5 parts per billion).[56] While often considered a nuisance by humans, these gelatinous animals are important in continental shelf food webs and are eaten by sea turtles, tuna and sunfish.

In aggregate both the literature I reviewed and Dr. Rice's analysis provide evidence that the very important planktonic ecosystem in the surface waters over the continental shelf and slope of the northern Gulf of Mexico was affected, at least for weeks to months, where and when oil slicks were

[52] Graham WM, Condon RH, Carmichael RH, D'Ambra I, Patterson HK, Linn LJ, Jr FJH (2010) Oil carbon entered the coastal planktonic food web during the Deepwater Horizon oil spill. Env Res Lett 5:045301
[53] Chanton JP, Cherrier J, Wilson RM, Sarkodee-Adoo J, Bosman S, Mickle A, Graham WM (2012) Radiocarbon evidence that carbon from the Deepwater Horizon spill entered the planktonic food web of the Gulf of Mexico. Env Res Lett 7:045303
[54] Ortmann AC, Anders J, Shelton N, Gong L, Moss AG, Condon RH (2012) Dispersed oil disrupts microbial pathways in pelagic food webs. PLoS One 7:e42548
[55] Almeda R, Wambaugh Z, Wang Z, Hyatt C, Liu Z, Buskey EJ (2013) Interactions between zooplankton and crude oil: toxic effects and bioaccumulation of polycyclic aromatic hydrocarbons. PLoS One 8:e67212
[56] Almeda R, Wambaugh Z, Chai C, Wang Z, Liu Z, Buskey EJ (2013) Effects of crude oil exposure on bioaccumulation of polycyclic aromatic hydrocarbons and survival of adult and larval stages of gelatinous zooplankton. PLoS One 8:e74476

present.[57] Concentrations of PAHs were measured that can have toxic effects on sensitive life stages marine organisms. Petroleum hydrocarbons were incorporated into planktonic food webs both as a food resource and as potentially toxic contaminants. Based on the evidence, it is reasonable to conclude that both lethal and sublethal effects on planktonic organisms occurred in near-surface waters. These effects included some that would be harmful to populations during or shortly after the periods when surface slicks occurred.

Oily "marine snow" formed in surface waters, providing a mechanism for deposition of oil on the seabed. As previewed in Section 4.1 observations and experiments demonstrated that oil and oil-dispersant mixtures caused the production of oily marine snow by phytoplankton and bacteria in surface waters.[58] Once losing buoyancy these hydrocarbon-containing organic aggregates were able to sink. Particularly in the vicinity of the Macondo wellhead, mineral sediment accumulated on the seabed far in excess of the normal sedimentation rates and these new deposits were enriched in petroleum hydrocarbons. This suggests that it was a result of biodeposition produced in the relatively turbid surface waters influenced by the Mississippi River plume and not just at the depths of deep-sea plume, where the seawater has very little suspended sediment. Impacts of this deposition are evaluated in Section 5.4.

5.3. Subsurface Waters

The reach of Macondo oil might have been carried by currents beyond were surface slicks were evident, thus expanding the geographic scope of potential environmental harm. Florida university scientists published a study[59] suggesting that this could be the case based on biological assays, two using test cultures of bacteria and another a protozoan (dinoflagellate). These test cultures were exposed to seawater samples collected from various locations in the Gulf to assay whether the ambient Gulf waters elicited sublethal toxic responses. The investigators interpreted the results as being consistent with the transport of dispersed oil from the Macondo well blowout onto or along the West Florida Shelf, well removed from where oil slicks were observed. Their test organisms exhibited toxic responses in the Big Bend area in May 2011 and off Tampa Bay during 2012, as much as two years after the capping of the blowout. They further suggested that organisms in contact with these waters might experience DNA damage that could lead to mutations and heritable genetic alterations. The study was strongly criticized by two ExxonMobil scientists who stated that the paper "makes extraordinary claims of environmental harm that are unsubstantiated, incorrect or misleading," detailing numerous criticisms of the methods and the precision, accuracy and interpretation of data.[60]

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[57] Rice, S.D. (2014) Toxicological Impact of the MC252 Blowout, Oil Spill, and Response. Expert Report submitted on behalf of the United States. U.S. v. BP Exploration & Production et al., 20.

[58] Passow U, Ziervogel K, Asper V, Diercks A (2012) Marine snow formation in the aftermath of the Deepwater Horizon oil spill in the Gulf of Mexico. Env Res Lett 7:035301

[59] Paul JH, Hollander D, Coble P, Daly KL, Murasko S, English D, Basso J, Delaney J, McDaniel L, Kovach CW (2013) Toxicity and mutagenicity of Gulf of Mexico waters during and after the Deepwater Horizon oil spill. Environ Sci Technol 47:9651-9659

[60] Prince RC, Parkerton TF (2014) Comment on "Toxicity and Mutagenicity of Gulf of Mexico Waters During and After the Deepwater Horizon Oil Spill". Environ Sci Technol 48:3591-3592

A companion computer modeling study sought to determine whether it was physically possible, given the prevailing ocean conditions during 2010, for subsurface oil to be transported southward along the West Florida Shelf toward the tip of the peninsula.[61] The model indicated that contaminants mixed throughout the water column where oil slicks reached off Destin, Florida beginning in June 2010 would have been off Tampa within a month and reached the Dry Tortugas in two months. By the end of September the hypothetical contaminant would have been broadly distributed in bottom waters of the West Florida Shelf, but at concentrations 10 to 100 times less than initial concentrations even assuming no degradation of the contaminant.

These articles only indicate a potential for subsurface transport of hydrocarbons on the continental shelf beyond areas where floating oil occurred and do not demonstrate actual harm. However, the controversy surrounding these results is illustrative of the lack of full resolution of actual harm caused by the Macondo well blowout at the present time as well as of the critical processes through which science is still working.

5.4. Seabed

Bottom habitats in offshore Gulf of Mexico ecosystems were contaminated by Macondo well oil by one or more of several potential mechanisms: (a) direct impingement of the deep hydrocarbon plume on the seabed; (b) biodeposition of organic aggregates from the deep hydrocarbon plume; (c) biodeposition emanating from organic aggregates or defecation by animal plankton in surface waters; (d) settling of oil-contaminated drilling fluids used during early attempts to kill the blowout; or (e) sinking of heavier byproducts resulting from burning of oil at the surface. The articles referenced below provide evidence for contamination of the seabed of the continental slope by petroleum hydrocarbons derived from the Macondo well blowout.

Deep-sea animals inhabiting bottom sediments were harmed over a large area. During fall 2010, severe reductions in abundance and diversity of populations of small invertebrate animals inhabiting bottom sediments extended to 3 kilometers from the wellhead in all directions, covering an area of about 24 square kilometers (9 square miles).[62] A zone of "moderate effects" was documented up to 17 kilometers to the southwest and 8.5 kilometers to the northeast of the wellhead, with the documented zone of impact covering 148 square kilometers (57 square miles). The intensity of effects was correlated with distance from the wellhead and sediment concentrations of total petroleum hydrocarbons, total PAHs and barium (a key ingredient of drilling fluid) and was unrelated to proximity to natural oil seeps. The results of subsequent sampling have not been reported in the scientific literature, but scientists reporting on the 2010 sampling opined that recovery rates were likely to be slow, on the order of decades or longer.

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[61] Weisberg RH, Zheng L, Liu Y, Murawski S, Hu C, Paul J (2014) Did Deepwater Horizon hydrocarbons transit to the west Florida continental shelf? Deep-Sea Res II http://dx.doi.org/10.1016/j.dsr2.2014.02.002

[62] Montagna PA, Baguley JG, Cooksey C, Hartwell I, Hyde LJ, Hyland JL, Kalke RD, Kracker LM, Reuscher M, Rhodes AC (2013) Deep-sea benthic footprint of the deepwater horizon blowout. PLoS One 8:e70540

Effects on other bottom dwelling organisms living on the deep seabed near the Macondo wellhead have been reported. Presentations at scientific symposia have described impacts on shelled amoeba-like organisms called foraminifera,[63] in the same area where the impacts on sediment-dwelling invertebrates were found. The foraminifera were just showing signs of recovery in 2012, but the most affected areas were still characterized by species that survive in low oxygen environments, reflective of the deposition of organic matter associated with the 2010 "dirty blizzard" event. Photographic observations of larger bottom dwelling animals (invertebrates and fishes) during August and September 2010 revealed very few species in areas close to the wellhead and carcasses of sea cucumbers and sea pens were observed nearby.[64] Remains of types of tunicates (similar to seasquirts) that live in the water column littered the bottom, likely casualties of the blowout.

Microbial processes in sediments were disrupted. In September-October 2010 the most heavily oil-impacted sediments were enriched in bacteria species with genetic sequences very similar to bacteria in the deep-sea hydrocarbon plume.[65] Activated genes indicated that bacteria were actively degrading hydrocarbons, including lower molecular weight aromatic hydrocarbons. PAHs in the sediments were not being degraded as rapidly, presenting longer-term contaminant exposure. Rates of microbial denitrification, an important process regulating the marine nitrogen cycle, were greater in more contaminated sediments and metabolites associated with denitrification had accumulated.[66]

Cold-water corals were harmed by the deposition of oily residues. At locations ranging from 200 to more than 2,000 meters along the continental slope of the northern Gulf of Mexico, hard carbonate substrates are exposed on the otherwise sediment-covered seafloor. Attached to these hard substrates live various species of corals adapted to these cold waters. Typically these corals are of a tree-like or fan-like form. Associated with the corals is a unique fauna that seeks shelter and sustenance afforded by the corals. Cold-water corals have recently been the focus of global conservation concern because they are susceptible to damage by expanding human intrusion into the deep sea, such as deep trawling, and are slow growing and often hundreds of years old. The Department of the Interior has required oil companies to survey and avoid deep-water coral communities in drilling exploration and production wells.

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[63] Selden CR, Hastings D, Schwing P, Brooks G, Hollander D (2014) Correlational changes in benthic foraminifera abundance and sedimentary redox conditions after the Deepwater Horizon Blowout event. Gulf of Mexico Oil Spill and Ecosystem Science Conference, Mobile, AL

[64] Valentine MM, Benfield MC (2013) Characterization of epibenthic and demersal megafauna at Mississippi Canyon 252 shortly after the Deepwater Horizon Oil Spill. Mar Pollut Bull 77:196-209

[65] Mason OU, Scott NM, Gonzalez A, Robbins-Pianka A, Balum J, Kimbrel J, Bouskill NJ, Prestat E, Borglin S, Joyner DC, Fortney JL, Jurelevicius D, Stringfellow WT, Alvarez-Cohen L, Hazen TC, Knight R, Gilbert JA, Jansson JK (2014) Metagenomics reveals sediment microbial community response to Deepwater Horizon oil spill. ISME J 8:1464-1475

[66] Scott NM, Hess M, Bouskill NJ, Mason OU, Jansson JK, Gilbert JA (2014) The microbial nitrogen cycling potential in marine sediments is impacted by polyaromatic hydrocarbon pollution. Front Microbiol 5:1-8

In November 2010, four months after the Macondo well was capped, corals inhabiting hard substrates at 1,370 meters depth and 11 kilometers (about 6 nautical miles) from the Macondo wellhead were observed by a remotely operated vehicle to be covered by brown flocculent material (Figure 7).[67] Coral colonies exhibited varying degrees of tissue loss, enlargement of hardened body parts, and excess mucous production, conditions not observed at other sites more than 22 kilometers (12 nautical miles) from the well. Brittle starfish that live commensally on the coral colonies also appeared injured. Analysis of petroleum biomarkers in that flocculent material led the researchers to conclude that the coral colonies at this site had been affected by the deep hydrocarbon plume from the Macondo well blowout. Scientists associated with firms conducting studies for the oil industry published a critique in the same journal indicating that the coral colony was deeper than the plume and that it could have been affected by a natural oil seep.[68] However, the demonstration of a mechanism for deposition of flocculent material containing oil below the overlying plume, as well as subsequently published evidence of Macondo oil contamination in bottom sediments collected near the coral colony[69] strengthens the investigators' original conclusion that the corals were affected by the Macondo well blowout. Furthermore, in November 2011, two additional sites were discovered where coral colonies showed clear signs of impact, one 6 kilometers (nautical miles) to the south of the Macondo wellhead at 1,560 meters depth and the other 22 kilometers (12 nautical miles) away between 1,850 and 1,950 meters depth.[70]

Figure 7. Cold-water coral with a commensal brittle star attached covered by brown flocculent material.

Recovery of cold-water corals is likely to be very slow. Radiocarbon dating of coral colonies indicated that they were approximately 460 years old,[71] thus recovery from damage would likely take a very long time. By December 2010 hydroids (branching colonies of hydra-like animals) began to colonize the affected part of the coral colonies and by March 2012 they covered most of

[67] White HK, Hsing P-Y, Cho W, Shank TM, Cordes EE, Quattrini AM, Nelson RK, Camilli R, Demopoulos AWJ, German CR, Brooks JM, Roberts HH, Shedd W, Reddy CM, Fisher CR (2012) Impact of the Deepwater Horizon oil spill on a deep-water coral community in the Gulf of Mexico. Proc Natl Acad Sci USA 109:20303-20308

[68] Boehm PD, Carragher PD (2012) Location of natural oil seep and chemical fingerprinting suggest alternative explanation for deep sea coral observations. Proc Natl Acad Sci USA 109:E2647

[69] White HK, Hsing P-Y, Cho W, Shank TM, Cordes EE, Quattrini AM, Nelson RK, Camilli R, Demopoulos AWJ, German CR, Brooks JM, Roberts HH, Shedd W, Reddy CM, Fisher CR (2012) Reply to Boehm and Carragher: Multiple lines of evidence link deep-water coral damage to Deepwater Horizon oil spill. Proc Natl Acad Sci USA 109:E2648

[70] Fisher CR, Hsing P-Y, Kaiser CL, Yoerger DR, Roberts HH, Shedd WW, Cordes EE, Shank TM, Berlet SP, Saunders MG, Larcom EA, Brooks JM (2014) Footprint of Deepwater Horizon blowout impact to deep-water coral communities. Proc Natl Acad Sci USA 10.1073/pnas.1403492111

[71] White HK, Hsing P-Y, Cho W, Shank TM, Cordes EE, Quattrini AM, Nelson RK, Camilli R, Demopoulos AWJ, German CR, Brooks JM, Roberts HH, Shedd W, Reddy CM, Fisher CR (2012) Reply to Boehm and Carragher: Multiple lines of evidence link deep-water coral damage to Deepwater Horizon oil spill. Proc Natl Acad Sci USA 109:E2648

the impacted parts of the corals.[72] This suggested that additional deterioration of the long-lived corals was likely.

There is potential harm to organisms living on the seabed of the continental shelf. Based on evidence for animals living in sediments and for cold-water corals, the accumulation of hydrocarbon contaminants and associated biological effects over at least 57 square miles of the continental slope are among the best documented harmful and long lasting impacts resulting from the Macondo well blowout at this time. These results demonstrated that petroleum hydrocarbons, normally thought to be buoyant and immiscible, can find their way to the seabed through biodeposition and other mechanisms. The same processes that resulted in deposition of surface hydrocarbons in deep Gulf of Mexico ecosystems were likely also in operation as oil slicks moved over the continental shelf (Figure 8). However, thus far there have been few published studies that evaluated sediment contamination or biological effects on bottom-dwelling organisms that might have resulted from the Macondo well blowout. Over 10,000 bottom sediment samples were collected during the Natural Resources Damage Assessment. Presumably, results from analyses conducted during the NRDA will eventually be published in the open scientific literature. Until then, it is premature to speculate about the extent and duration of hydrocarbon contamination of continental shelf sediments and the actual harm that resulted.

Figure 8. Potential pathways for oil to reach bottom sediments (NOAA).

One particular issue regarding effects on the seabed of the continental shelf that has been addressed is whether the deposition of oil exacerbated seasonal hypoxia, or the notorious Dead Zone, that forms during the summer in the bottom waters of the inner shelf, primarily along Louisiana. A possible oil degradation signal in bottom waters was observed during the annual hypoxia survey during July 2010. It was manifest in the relationship between concentrations of dissolved oxygen and concentrations of dissolved inorganic carbon.[73] This anomaly was observed in the region off Grand Isle, which had greater exposure to floating oil, but not along the whole Louisiana shelf. Furthermore, the anomaly was not found during 2011 and

[72] Hsing P-Y, Fu B, Larcom EA, Berlet SP, Shank TM, Govindarajan AF, Lukasiewicz AJ, Dixon PM, Fisher CR (2013) Evidence of lasting impact of the Deepwater Horizon oil spill on a deep Gulf of Mexico coral community. Elementa Sci Anthop 1:000012

[73] Hu X, Cai W-J, Rabalais NN, Xue J (2014) Coupled oxygen and dissolved inorganic carbon dynamics in coastal ocean and its use as a potential indicator for detecting water column oil degradation. Deep-Sea Res II http://dx.doi.org/10.1016/j.dsr2.2014.01.010

2012, suggesting that there was too little oil remaining to contribute to bottom oxygen depletion. While the degree to which bottom hypoxia intensified or expanded was not determined, the anomaly illustrates the compounding effects of multiple stressors from human activities on ecosystems. In such cases it is very challenging, if not impossible, to proportionally assign harm.

5.5. Fish

Given the previous discussion of the fate of hydrocarbons released by the Macondo blowout it stands to reason that fish living in close association with either the surface waters or the seabed of offshore Gulf ecosystems were the most likely to be harmed. Indeed, there is scientific evidence concerning the effects on fish embryos and larvae found in offshore surface waters and on juveniles and adults of fish residing at the seabed on the continental shelf and slope.

Exposure of embryos and larvae of oceanic fish resulted in impairment of heart function and swimming speed that potentially could reduce the size of a year class. In the decades since the Exxon Valdez oil spill in Alaska, developing fish embryos have been shown to be especially vulnerable to the toxicity of crude oil. Tests performed on embryos of zebrafish, a small fish that occurs neither off Alaska nor the Gulf of Mexico but is a standard model organism in developmental biology, showed that the toxicity to heart function of weathered Macondo well oil is comparable to weathered Alaska North Slope crude oil, the type released by the Exxon Valdez.[74] Similar tests using weathered Macondo oil collected by oil skimmers were conducted involving exposure to yellowfin tuna, Southern bluefin tuna and yellow tail amberjack.[75] The first species spawns in the open waters of the northern Gulf of Mexico and the other two are species that do not occur in the Gulf of Mexico but are closely related to species that spawn in the Gulf: the Atlantic bluefin tuna and greater amberjack, respectively. These open ocean fish are very sensitive to physical contact, thus only a few broodstocks exist throughout the world to allow this experimentation.

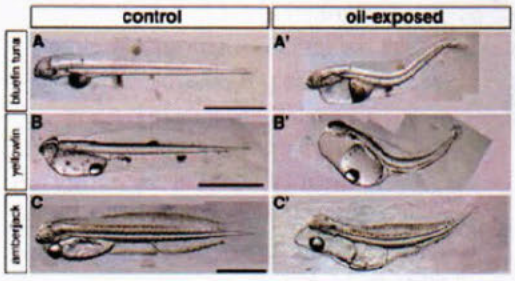

Figure 9. Microscopic photographs showing edema of the pericardium and other malformations in larvae exposed to oil in contrast to controls.

Concentrations of PAHs that buoyant fish embryos might realistically experience where there were Macondo oil slicks (1-15 parts per billion) caused dose-dependent defects in heart function in larvae of all three species tested. Disruption of the circulatory system culminating in fluid accumulation (edema) in the pericardium and malformation of fins (Figure 9) was associated with the heart function responses. The specific physiological

[74] Incardona JP, Swarts TL, Edmunds RC, Linbo TL, Aquilina-Beck A, Sloan CA, Gardner LD, Block BA, Scholz NL (2013) Exxon Valdez to Deepwater Horizon: Comparable toxicity of both crude oils to fish early life stages. Aquatic Toxicology 142–143:303-316

[75] Incardona JP, Gardner LD, Linbo TL, Brown TL, Esbaugh AJ, Mager EM, Stieglitz JD, French BL, Labenia JS, Laetz CA, Tagal M, Sloan CA, Elizur A, Benetti DD, Grosell M, Block BA, Scholz NL (2014) Deepwater Horizon crude oil impacts the developing hearts of large predatory pelagic fish. Proc Natl Acad Sci USA 111:E1510-E1518

effects on heart muscles were demonstrated in a companion study.[76] The hydrocarbon composition of the experimental exposures matched well that of Gulf surface waters contaminated by the blowout. Bluefin tuna was the most sensitive species with concentrations less than one part per billion causing edema in half of the larvae exposed. This is noteworthy because the main spawning grounds for the Atlantic bluefin tuna are in the northern Gulf of Mexico and its current population is at a historic low. Thus, there is the potential that the oil that prevailed for three months on the offshore surface waters could have reduced the larval recruitment into the 2010 year class for this species.

Similar effects on pericardial and yokesack edema in mahi-mahi (dolphinfish) were found in experimental exposures to water-accommodated Macondo oil skimmed from the Gulf surface.[77] In addition, exposure of juvenile mahi-mahi or of embryos and larvae raised to juveniles reduced the swimming speed of the juvenile fish. Once again, concentrations that elicited effects were quite low, as low as 1.2 parts per billion of PAHs for exposure of embryos and larvae. Swimming performance is quite critical for the survival these famously fast swimming fish as it affects their ability to catch food and avoid predators.

Exposure to sediment contamination was the likely cause of petroleum contaminants in fishes at the shelf edge with potential harm to their populations. Several species of bottom-dwelling fish species along the continental shelf edge north of the Macondo well were found to contain elevated concentrations of PAHs in their liver and PAH metabolites in their bile during 2011.[78] The levels were higher than in fish of the same species collected outside of the influence of the blowout and were lower in samples collected in 2012 than in 2011. The relative composition of PAHs in liver samples was highly comparable to that in oil collected from the leaking wellhead and no to other potential PAH sources. This evidence indicates that these bottom-dwelling fishes had accumulated hydrocarbon contaminants from the Macondo well blowout and that contamination dissipated over time. The species affected include red snapper, which congregates around hard-bottom outcropping; southern hake, which forages in bottom sediments in search of prey; and tilefish, which create burrows into semi-consolidated sediments. Fish at sites lying under the footprint of frequent oil slicks were most affected, including along the margins of the DeSoto Canyon. This suggests that bottom sediments were contaminated by the deposition of hydrocarbons from surface waters, although the upwelling of subsurface hydrocarbon plumes may also have contributed. A higher than normal incidence of skin lesions was also found in the most affected regions. This incidence also declined from 2011 to 2012, suggesting that development of lesions was in some way connected to exposure or uptake of PAHs or other hydrocarbons.

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[76] Brette F, Machado B, Cros C, Incardona JP, Scholz NL, Block BA (2014) Crude oil impairs cardiac excitation-contraction coupling in fish. Science 343:772-776

[77] Mager EM, Esbaugh AJ, Stieglitz JD, Hoenig R, Bodinier C, Incardona JP, Scholz NL, Benetti DD, Grosell M (2014) Acute embryonic or juvenile exposure to Deepwater Horizon Crude oil impairs the swimming performance of Mahi-Mahi (*Coryphaena hippurus*). Environ Sci Technol 48:7053-7061

[78] Murawski SA, Hogarth WT, Peebles EB, Barbeiri L (2014) Prevalence of external skin lesions and polycyclic aromatic hydrocarbon concentrations in Gulf of Mexico fishes, post-Deepwater Horizon. Trans Am Fish Soc 143:1084-1097

6. COASTAL ECOSYSTEMS

6.1. Modes of Impacts

As reviewed in Section 4.3 at least 1,138 miles of shoreline of the northern Gulf of Mexico coast—from Galveston, Texas to St. George Island on the Florida Panhandle—experienced oiling during 2010.[79] The oil that eventually stranded on the shoreline rose through 1,500 meters of seawater and was subjected to further dissolution, evaporation, and degradation by sunlight and microbes before it reached the coast from 40 to 300 miles away. Most oil remaining was in the form of a thick viscous emulsion, containing up to 60% water, rather than fresh, liquid crude oil. This sticky emulsion tended to adhere to birds and other organisms exposed at the air-water surface or in the intertidal zone. On some beaches the oil penetrated several centimeters into the sand and sand was deposited on top of it by waves and tides. Over time, semi-cohesive sand-oil residues developed in the form of balls, patties and continuous mats. Extensive oil-residue mats, consisting predominantly of sand and in some places extending more than a football field in length, were exposed a year or more after the oil came ashore. In marshes, the oil tended to stick to the blades of grass or pool on the surface without immediately sinking into the marsh soil. Various actions taken to control floating oil or remove it from shorelines also had consequences for coastal ecosystems.

This section assesses the actual or potential harm to these shorelines, including marshes that represented approximately 45% of the oiled shorelines. Gulf coastal environments are of national significance not only as popular recreational resources, but also for the wildlife and biological productivity they support and their storm protection and water quality benefits. About one-half of the coastal wetlands in the United States lie within the stretch of the affected shorelines along the Texas to Florida coast. Harm is also assessed for the shallow-water ecosystems within the sounds, bays and bayous that lie within the outer Gulf coastline.

6.2. Beaches and Shorelines

The northern Gulf of Mexico coast does not have natural rocky shorelines, and over half of the affected shorelines observed during the response were beaches of one form or another. These included wide sandy beaches exposed to the open Gulf and narrower zones in more protected waters comprised of finer and muddier sands and shell. Even the beaches exposed to the open Gulf vary substantially as a result of wave exposure and the grain size and mineral composition of the sand. Anyone who has been both to Destin, Florida and Grand Isle, Louisiana would appreciate the differences in Gulf beaches. In some places, old marsh sediments, composed of consolidated clay and root matter, are exposed along beaches where shorelines are retreating.

The stranding of oil on sandy beaches greatly limited the access to these beaches for recreation. Precautionary closures and perceptions of tourists and recreation-seekers resulted in real

[79] Michel J, Owens EH, Zengel S, Graham A, Nixon Z, Allard T, Holton W, Reimer PD, Lamarche A, White M, Rutherford N, Childs C, Mauseth G, Challenger G, Taylor E (2013) Extent and degree of shoreline oiling: Deepwater Horizon oil spill, Gulf of Mexico, USA. PLoS One 8:e65087

economic harm, but this lies outside of the scope of this assessment. Harm to ecosystems and valued resources associated with shorelines, including effects on the habitats of birds and sea turtles have, to this point, received little quantitative evaluation in the scientific literature. Hopefully, this will change as more NRDA results are available in the public domain.

Oil residue diminished over time, reducing hydrocarbon exposure, but was still present on some beaches and marshes in 2014. As a result of physical forces that disaggregate and transport oil residue and, potentially further biodegradation, the degree of oiling diminished over the next two years.[80] Of the 360 kilometers of heavily oiled shores in 2010, only 6.4 kilometers remained in the heavily oiled category in May 2012. Comparable numbers for shoreline categorized as moderately oiled are 222 kilometers in 2012 versus 17.5 in 2011. The sand-oil amalgamations that formed as balls to mats on beaches are denser than water and do not float away. These residues were continuing to cause beach re-oiling three years after initial oiling along the Alabama-Florida coast as they are uncovered and transported during storms.[81] PAHs associated with this lingering contamination were taken up by the small Coquina clams living in the surf zone on Florida Panhandle beaches. Monitoring revealed that PAH concentrations declined over two years, but were detectible for a longer period in the clam tissues than in the sand itself. It should be emphasized, however, that sand-oil residues and even sizeable mats are still being found in 2014.[82]

Oil removal efforts produced negative impacts as well as benefits. Massive effort was expended to remove stranded oil from shorelines where, on balance, it was deemed necessary by the clean-up assessment. While this significantly reduced the potential for oil to be re-transported to shorelines not yet affected, as well as the amount of residual oil, in some cases physical removal activities resulted in another set of impacts. These include those associated with vehicle traffic on beaches and dunes and the scraping, grading and deep cleaning of shoreline sediments. Deep cleaning, involving the sieving of beach sands to remove oiled residue balls and patties, tended to break up these residues in the process, diminishing the efficacy of method, at least from a toxic exposure point of view.[83] This process also altered the shell-sand habitat matrix that affects the habitats and sediment dynamics of beaches.

Barrier sand berms constructed to protect coastal wetlands from oil exposure had both positive and potentially harmful consequences. Another response effort that may have potential environmental consequences is the construction of barrier sand berms that were built in

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[80] Michel J, Owens EH, Zengel S, Graham A, Nixon Z, Allard T, Holton W, Reimer PD, Lamarche A, White M, Rutherford N, Childs C, Mauseth G, Challenger G, Taylor E (2013) Extent and degree of shoreline oiling: Deepwater Horizon oil spill, Gulf of Mexico, USA. PLoS One 8:e65087

[81] Dalyander PS, Long JW, Plant NG, Thompson DM (2014) Assessing mobility and redistribution patterns of sand and oil agglomerates in the surf zone. Mar Pollut Bull 80:200-209

[82] Blair K (2014) 1,783 pounds of BP oil removed from seashore. Pensacola News Journal, http://on.pnj.com/1rDYXFx Gannett, Pensacola, FL

[83] Hayworth JS, Clement TP, Valentine JF (2011) Deepwater Horizon oil spill impacts on Alabama beaches. Hydrology and Earth System Sciences 15:3639-3649

an attempt to obstruct oil from entering sounds and bays of the Louisiana and Alabama coasts.[84] The long-term benefits and detriments of these engineering actions to obstruct floating oil await determination. Sand to build the berms west of the Mississippi River was pumped from the lower river and has since been used as basis for strategic restoration of Shell, Pelican and Scofield barrier islands. Sand to build the barrier berms along the Chandeleur Islands was dredged from offshore where the potential for harm was greater and their restoration benefits are less certain because much of the sand was dissipated by subsequent tropical storms. Somewhat similar actions were taken to close "Katrina Gap" on Dauphin Island, Alabama.

6.3 Marshes and Mangroves

Throughout the Macondo well blowout there was great concern about the potential long-term harm that would result should oil encounter the extensive coastal marshes and mangroves in the region. Not only is oil difficult to remove from wetlands without risking greater damage, but based on studies of other oil spills, recovery of wetland plants and animals can take 8 to 40 years.[85] Moreover, the extensive wetlands create and define much of the geography in the region, a geography that is rapidly shrinking as a result of an array of human and natural causes. Some research results on the effects of weathered Macondo well oil on marsh plants and the associated ecosystem have been published, but long-term studies are continuing as part of the NRDA and Gulf of Mexico Research Initiative, as well as through independent efforts.

Impacts on marshes depend on the degree of oiling.[86] The vast majority of the wetlands oiled were in Louisiana, with marshes around the Mississippi River passes, Barataria Bay (particularly Bay Jimmy and Bay Batiste), Terrebonne Bay and Chandeleur Sound receiving the most extensive and heaviest oiling. The effects on wetland plants depended on the degree of oiling, the plant species and the mode of exposure. Near Ocean Springs along Mississippi Sound, moderate oiling caused only a short term decrease in the rate of photosynthesis in saltmarsh cordgrass (*Spartina alterniflora*).[87] In Louisiana, heavy oiling of marsh vegetation in Barataria caused the complete mortality of both cordgrass and black needlerush (*Juncus roemerianus*).[88] The common reed (*Phragmites australis*) that dominates the freshwater marshes around the Mississippi River delta passes had a high tolerance to weathered Macondo well oil.[89] Moderate oiling impacted cordgrass less severely than it did needlerush, which experienced diminished mass and density of stems. Soil-

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[84] Martínez ML, Feagin RA, Yeager KM, Day J, Costanza R, Harris JA, Hobbs RJ, López-Portillo J, Walker IJ, Higgs E, Moreno-Casasola P, Sheinbaum J, Yáñez-Arancibia A (2011) Artificial modifications of the coast in response to the Deepwater Horizon oil spill: quick solutions or long-term liabilities? Front Ecol Environ 10:44-49

[85] Mendelssohn IA, Andersen GL, Baltz DM, Caffey RH, Carman KR, Fleeger JW, Joye SB, Lin Q, Maltby E, Overton EB, Rozas LP (2012) Oil impacts on coastal wetlands: implications for the Mississippi river delta ecosystem after the Deepwater Horizon oil spill. BioScience 62:562-574

[86] Discussion of degree of shoreline oiling as "low," "moderate" or "heavy" in sections on shoreline impacts reference specific definitions of oiling developed during the SCAT process. *See* Michel Dep. at 106-108

[87] Wu W, Biber PD, Peterson MS, Gong C (2012) Modeling photosynthesis of *Spartina alterniflora* (smooth cordgrass) impacted by the Deepwater Horizon oil spill using Bayesian inference. Env Res Lett 7:045302

[88] Lin Q, Mendelssohn IA (2012) Impacts and recovery of the Deepwater Horizon oil spill on vegetation structure and function of coastal salt marshes in the northern Gulf of Mexico. Environ Sci Technol 46:3737-3743

[89] Judy CR, Graham SA, Lin Q, Hou A, Mendelssohn IA (2014) Impacts of Macondo oil from Deepwater Horizon spill on the growth response of the common reed *Phragmites australis*: A mesocosm study. Mar Pollut Bull 79:69-76

oiling affected all three species of marsh plants. Although it did not kill the common reed, it reduced both its vegetative and underground biomass. Where there was relatively low soil oiling, cordgrass recovered through vegetative growth from underground rhizomes. Where oiling was heavier, both cordgrass and needlerush died and did not regrow, either because the rhizomes were killed by the toxic components of the oil or smothering or because of chronic re-oiling of new shoots by tidal fluctuations.

Where oiling was heavy the harm is long-term if not permanent. While marsh grass vegetation largely recovered within 18 months under low to moderate oiling, where heavy oiling resulted in complete plant mortality the denuded soils eroded away causing an episodic shoreline retreat (Figure 10).[90] Decaying rhizomes and roots and perhaps the oil itself weakened the strength of the soil, causing it to be undercut by waves.[91] Sections of the marsh shore collapsed, taking with them living marsh plants in a cascading process that may take two or more years to completely unfold. There is every reason to think that this marsh loss is permanent, due to high rates of relative sea level rise and continued wave erosion in the region, marshes in these areas are not expanding; they are contracting. Accordingly, there is no "natural" mechanism to reverse the marsh loss caused by the oil spill. It would take large-scale restoration measures, such as placement of dredged sediment or river diversions, to reverse this trend and recover the lost marshland. Furthermore, the longer such restoration efforts are put off the harder and more expensive they are to employ.

Figure 10. Top: Marsh vegetation (mostly saltmarsh cordgrass) killed by oiling in Barataria Bay (P.J. Hahn photo). Bottom: remnants of black mangroves on Cat Island, which had served as a bird rookery, in Barataria Bay in 2012.

Similar habitat losses have been observed for heavily oiled black mangroves (*Avicennia germinans*) at Cat Island in Barataria Bay.[92] This is under investigation in the NRDA, but studies have not yet been reported in the scientific literature. Black mangroves are at the northern end of their geographic range in southeastern Louisiana, but prior to 2010 had been expanding because of the declining frequency of killing freezes.[93] Even small losses of mangroves could potentially cause substantial harm because these small trees provide nesting sites for brown pelicans, roseate

[90] Silliman BR, van de Koppel J, McCoy MW, Diller J, Kasozi GN, Earl K, Adams PN, Zimmerman AR (2012) Degradation and resilience in Louisiana salt marshes after the BP–Deepwater Horizon oil spill. Proc Natl Acad Sci USA 109:11234-11239

[91] McClenachan G, Turner RE, Tweel AW (2013) Effects of oil on the rate and trajectory of Louisiana marsh shoreline erosion. Env Res Lett 8:044030

[92] Marshal B (2014) 2014 BP oil spill choked off important pelican nesting sites on Louisiana coast The Lens, New Orleans, LA, http://thelensnola.org/2014/04/11/bp-oil-spill-choked-off-important-pelican-nesting-sites/

[93] Giri C, Long J, Tieszen L (2011) Mapping and monitoring Louisiana's mangroves in the aftermath of the 2010 Gulf of Mexico oil spill. J Coast Res 10.2112/JCOASTRES-D-11-00028.1:1059-1064

spoonbills and other birds, and important habitat for aquatic organisms.

Chronic contamination of heavily impacted wetlands will continue into the future. Oil remaining in marshes receiving low to moderated doses degraded significantly over the first 18 months due to removal by tidal exchange and the proliferation of oil-degrading bacteria.[94,95] Even concentrations of the more recalcitrant PAHs declined over this period. However, particularly in heavily oiled marshes, degradation of oil in wetland soils is slowed by several factors. A residual viscous mass will develop a crust as it weathers, retaining less-degraded oil inside. Oil that seeps into the marsh soils biodegrades more slowly because of insufficient oxygen within the soil.[96] As a result, remaining petroleum hydrocarbons are currently still detectable visually, by odor, and through chemical analysis where wetlands soils were heavily contaminated with weathered Macondo well oil.

Marsh oiling also affected the associated animal communities. In heavily oiled marshes in Mississippi Sound, Chandeleur Sound and Barataria Bay, small, shelled protozoa, called foraminifera, that live in marsh soil were reduced in abundance and were restricted to the surface of the marsh.[97] Where there was a more modest exposure to oil, the populations of foraminifera boomed, probably because they were feeding on bacteria whose growth was stimulated by the oil. At sites in Louisiana and Mississippi, populations of various arthropods (crustaceans, insects, spiders, etc.) were negatively affected by oiling.[98] Fiddler crab burrows were fewer and populations of terrestrial insects and spiders were suppressed, even in seemingly unoiled stands of plants within the oiled areas. One year later populations of these arthropods had largely recovered. Fiddler crabs have been shown to rapidly bioaccumulate hydrocarbons from Macondo oil.[99]

Oil-related impacts compound the effects of other factors causing severe wetland loss. The visual observations of substantial, and in some areas persistent, oiling of coastal wetlands, particularly in the Mississippi Deltaic Plain of Louisiana, reinforced by the scientific evidence of contamination and biological effects, substantiate that there was actual harm. This harm has to be considered in light of the chronic factors that are currently resulting in the deterioration of these wetland ecosystems: high rates of subsidence due to oil and gas extraction as well as natural factors, interruption of sediment supply from the Mississippi River by levees and dams,

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[94] Beazley MJ, Martinez RJ, Rajan S, Powell J, Piceno YM, Tom LM, Andersen GL, Hazen TC, Van Nostrand JD, Zhou JZ, Mortazavi B, Sobecky PA (2012) Microbial community analysis of a coastal salt marsh affected by the Deepwater Horizon oil spill. PLoS One 7:e41305

[95] Mahmoudi N, Porter TM, Zimmerman AR, Fulthorpe RR, Kasozi GN, Silliman BR, Slater GF (2013) Rapid degradation of Deepwater Horizon spilled oil by indigenous microbial communities in Louisiana saltmarsh sediments. Environ Sci Technol 47:13303-13312

[96] DeLaune RD, Wright AL (2011) Projected impact of Deepwater Horizon oil spill on U.S. gulf coast wetlands. Soil Sci Soc Am J 75:1602-1612

[97] Brunner CA, Yeager KM, Hatch R, Simpson S, Keim J, Briggs KB, Louchouarn P (2013) Effects of oil from the 2010 Macondo well blowout on marsh foraminifera of Mississippi and Louisiana, USA. Environ Sci Technol 47:9115-9123

[98] McCall BD, Pennings SC (2012) Disturbance and recovery of salt marsh arthropod communities following BP Deepwater Horizon oil spill. PLoS One 7:e32735

[99] Chase DA, Edwards DS, Qin G, Wages MR, Willming MM, Anderson TA, Maul JD (2013) Bioaccumulation of petroleum hydrocarbons in fiddler crabs (*Uca minax*) exposed to weathered MC-252 crude oil alone and in mixture with an oil dispersant. Sci Total Environ 444:121-127

channelization by oil and gas and navigation canals, impoundments, invasive species, hurricanes and droughts, and accelerated sea-level rise.[100] These natural and human-induced factors have resulted in a loss of approximately 2,100 square miles (5,400 square kilometers) of coastal wetlands between 1930 and 2010 in Louisiana alone. It might be argued that the documented erosion of oiled marsh edges pales in comparison to the acres lost every year to these other factors. However, the harm from Macondo well oiling is very likely more than simply additive but, instead, compounds the wetland-loss crisis by accelerating losses due to other factors and further diminishing their sustainability and resistance to future disturbances.

6.4 Sounds, Bays and Bayous

Of course, the weathered hydrocarbon residual that reached coastal wetlands passed through shallow sounds, bays and bayous of the northern Gulf of Mexico on their way, exposing the sandy and muddy bottom habitats where shrimp, fish, oysters, birds and bottlenose dolphins rely on these highly productive waters. However, few reports in the scientific literature address real or potential harm to these protected, shallow-water ecosystems.

Marsh oiling reduced the growth rate of shrimp living nearby. The complex of wetland and shallow-water habitats along the northern Gulf coast is particularly important as nurseries for brown (*Farfantepenaeus aztecus*) and white (*Litopenaeus setiferus*) shrimp that are the basis of the Gulf's most valuable fishery. Field experiments showed that a year after oil reached marshes in Bay Jimmy in Barataria Bay, the growth rates of shrimp deployed in the cages near heavily and moderately oiled marshes were less than half those near unoiled and lightly oiled marshes[101]. Growth rates of brown shrimp were negatively correlated with the concentration of PAHs in bottom sediments, which average about 600 parts per billion near oiled marshes.

Fish chronically exposed to oil-contaminated sediments demonstrated sublethal effects that potentially could result in harm at the population level. The Gulf killifish (*Fundulus gandis*) is a small ubiquitous denizen of Gulf salt marshes. It is not caught for human consumption but is a very important prey of larger fish. It is widely used for bait along the Gulf Coast, where it is commonly referred to as cocahoe minnow. Killifish are also commonly used as a model test organism for other toxic responses in bony fishes generally. Killifish collected at Grand Terre in lower Barataria Bay, near marshes that had been heavily oiled, showed increased genetic activity in pathways that regulate a fish's response to PAHs in their liver, while those collected at unoiled sites along the Mississippi and Alabama coasts did not.[102] This indicates a biological response to the stress of PAH exposure even though elevation of PAH concentrations in fish tissues and ambient seawater were

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[100] Mendelssohn IA, Andersen GL, Baltz DM, Caffey RH, Carman KR, Fleeger JW, Joye SB, Lin Q, Maltby E, Overton EB, Rozas LP (2012) Oil impacts on coastal wetlands: implications for the Mississippi river delta ecosystem after the Deepwater Horizon oil spill. BioScience 62:562-574

[101] Rozas L, Minello T, Miles MS (2014) Effect of Deepwater Horizon oil on growth rates of juvenile penaeid shrimps. Estuaries and Coasts 10.1007/s12237-013-9766-1:1-12

[102] Whitehead A, Dubansky B, Bodinier C, Garcia TI, Miles S, Pilley C, Raghunathan V, Roach JL, Walker N, Walter RB, Rice CD, Galvez F (2012) Genomic and physiological footprint of the Deepwater Horizon oil spill on resident marsh fishes. Proc Natl Acad Sci USA 109:20298-20302

not detected. The seawater from Grand Terre also caused increased expression of a protein indicative of PAH exposure in fish gills in association with elevated incidence of hyperplasia (unusual proliferation of cells) and other histological anomalies. The researchers stated that even though body burdens of PAH contaminants were not high (compared to concentrations that might merit disallowing sale of commercial species), exposure could result in physiological impairment persisting at least two months after initial exposures. Other scientists funded by BP published a criticism of this article, claiming that (a) the measured seawater concentrations were not consistent with the observed biological responses and (b) chemicals other than those from Macondo well oil could have caused these responses.[103]

Some of the original researchers later reported gene expression related to PAH exposure and stress response in the gill, liver, intestine and kidney of killifish at Grand Terre for over one year following the Macondo oil landfall, but not at the unaffected sites.[104] Laboratory exposure of killifish embryos to sediments collected from Grande Terre, but not the reference sites, resulted in developmental abnormalities. The researchers stated that: "the data are predictive of population-level impacts in fish exposed to sediments from oiled locations along the Gulf of Mexico coast." Once again, another scientist supported by BP published a critique of these new results, conceding that exposure to oiled sediments adversely affected the survival potential of larvae hatching from exposed eggs, but challenging whether these results are predictive of population-level impacts. A key distinction is between "demonstrate" and "predict." While actual harm at the level of an individual fish has been demonstrated, harm at the population level has not and should be regarded as potential rather than actual.

There was potential harm to oyster stocks due to oil and related response actions, but the causes of oyster declines are not yet fully resolved. The Eastern Oyster (*Crassostrea virginica*) is another key organism that is not only economically valuable but plays important ecological roles in sounds, bays and bayous by building habitat used for shelter and forage by other animals, regulating water quality by filtering large volumes of water, and protecting shorelines from waves, storm surges and erosion. As of the date of this report, I am unaware of any reports, scientific or otherwise, of Macondo oil directly killing oysters. There was no evidence in published literature of elevated levels of PAHs in oyster tissue in Mississippi Sound during and after the spill.[105, 106] The nutritional and reproductive conditions of the oysters were also not exceptional for the environments in which they were collected. Levels of carbon-13 in oyster muscle suggested that oysters in Mobile Bay and eastern Mississippi Sound had been feeding on natural organic material and not oil (see Section 5.2 for a discussion on how stable and radioisotopes of carbon are used to

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[103] Jenkins KD, Branton MA, Huntley S (2012) CYP1A expression fails to demonstrate exposure–response relationship. Proc Natl Acad Sci USA 109:E678

[104] Dubansky B, Whitehead A, Miller JT, Rice CD, Galvez F (2013) Multitissue molecular, genomic, and developmental effects of the Deepwater Horizon oil spill on resident Gulf killifish (*Fundulus grandis*). Environ Sci Technol 47:5074-5082

[105] Soniat TM, King SM, Tarr MA, Thorne MA (2011) Chemical and physiological measures on oysters (*Crassostrea virginica*) from oil-exposed sites in Louisiana. J Shellfish Res 30:713-717

[106] Xia K, Hagood G, Childers C, Atkins J, Rogers B, Ware L, Armbrust K, Jewell J, Diaz D, Gatian N, Folmer H (2012) Polycyclic aromatic hydrocarbons (PAHs) in Mississippi seafood from areas affected by the Deepwater Horizon oil spill. Environ Sci Technol 46:5310-5318

trace oil in food chains).[107] However, the areas from which these oysters were collected were not subject to heavy or persistent oiling of the level seen in parts of Barataria Bay, for example. But the results do not indicate that oysters were not exposed to oil, rather they imply oysters did not consume enough oil-derived material to be detectable compared to natural diet. Carbon-12 and carbon-14 levels in marsh mussels and barnacles collected in Barataria Bay also indicated that these other filter feeders had derived their nutrition from natural sources rather than petroleum contaminants.[108]

Despite the lack of published evidence of direct mortality of oysters due to oiling or bioaccumulation of petroleum hydrocarbons, there is continued concern that declines in the abundance of market-sized oysters and oyster spat (small oysters developing after larvae settle) on public grounds in the Breton Sound and Barataria Bay areas of Louisiana reflect impacts of oil or freshwater releases from diversions and siphons along the Mississippi River in an effort to keep incoming oil out of sensitive marshes and estuaries.[109] Extensive reductions of spat recruitment have occurred in some areas since 2010 and continued into 2013; in other areas spat had poor survival. Commercial harvests fell sharply in 2012 and 2013. Assessments are ongoing of the causes of these declines, including oil and response actions in addition to other factors such as river discharge and other climatic variations, Hurricane Isaac, habitat quality, diseases and harvest pressure.

6.5 Birds and Marine Mammals

The U.S. Fish and Wildlife Service maintained a consolidated "body count" of impacted birds, sea turtles and marine mammals collected during the Macondo well blowout and in the months that followed, noting the numbers collected alive and dead and whether they were visibly oiled (Table 2). Over half of the birds were collected in Louisiana and nearly three-quarters of the mammals were collected in Mississippi. The majority of the sea turtles collected dead were in Mississippi and Louisiana.

Table 2. Deepwater Horizon Response consolidated fish and wildlife collection through April 14, 2011.[110]

	Collected Alive		Collected Dead	
	Total	Visibly Oiled	Total	Visibly Oiled
Birds	3,046	2,086	6,147	2,303
Sea Turtles	536	456	613	18

[107] Carmichael RH, Jones AL, Patterson HK, Walton WC, Pérez-Huerta A, Overton EB, Dailey M, Willett KL (2012) Assimilation of oil-derived elements by oysters due to the Deepwater Horizon oil spill. Environ Sci Technol 46:12787-12795

[108] Fry B, Anderson LC (2014) Minimal incorporation of Deepwater Horizon oil by estuarine filter feeders. Mar Pollut Bull 80:282-287

[109] Louisiana Department of Wildlife & Fisheries (2013) Oyster Stock Assessment Report of the Public Oyster Seed Areas of Louisiana Seed grounds and Seed Reservations. Oyster Data Report Series, No. 19, Baton Rouge, LA

[110] U.S. Fish and Wildlife Service (2011) Deepwater Horizon Response Consolidated Fish and Wildlife Collection Report http://www.fws.gov/home/dhoilspill/collectionreports.html

Mammals	13	2	157	10

Actual bird mortalities were substantially greater than the number of carcasses collected and potentially depleted populations of some bird species in the northern Gulf of Mexico. Of course, the numbers in Table 2 do not tell the whole story in terms of the impact of the Macondo well blowout. The cause of death may be due to factors other than oil from the blowout; even those animals visibly oiled could have succumbed to other causes and were oiled incidentally. On the other hand, not all animals affected by the blowout oil were collected. A forthcoming journal article estimated the total acute bird mortality using two different models, one based on the distribution of carcass sampling and the other on the probability of exposure to oil.[111] The mean estimate of bird deaths was 600,000 for the first model with 95% certainty that deaths were between 320,000 to 1,200,000. For the second model the mean was 800,000 bird deaths with a 160,000 to 1,900,000 range for confidence range. While it is often assumed that the number of birds killed by a more modest oil spill may be as much as ten times greater than the number of birds collected, these model estimations suggest that deaths might be 100 times greater. This could be because of the vast area of exposure to oil that makes detection difficult and the conditions prevailing at the time that tended to move carcasses offshore. These estimates of potential mortality are based on a number of assumptions and better resolution of the number of bird deaths will have to await release of analyses undertaken in the NRDA and of publications by other researchers. It is reasonable to conclude, however, that actual bird mortalities were substantially greater than the number of dead birds collected. Also, parallel model estimates of bird deaths farther offshore, affecting species such as the sooty tern and storm petrel, are awaiting publication.[112]

For coastal birds, at least, it is likely that smaller birds are disproportionately underrepresented in the consolidated collection data. The models suggest that laughing gulls, royal terns, northern gannets, and brown pelicans were the most affected populations. The models projected that 36% of the laughing gulls in the northern Gulf of Mexico could have been killed and, indeed, there were substantial declines in laughing gulls in the subsequent Christmas Bird Counts. Also, an estimated 25% of the North American colonies of northern gannets had migrated into the portions of the Gulf of Mexico containing floating oil and the timing made immature birds most susceptible.[113] Although there have been popular press reports of an apparent rebound of brown pelican colonies in the years following the Macondo well blowout, there are no scientific journal articles yet that address the long-term consequences of the blowout on Gulf Coast bird populations. Furthermore, population-level effects are inherently difficult to assess because of high variability, migrations and multiple factors affecting the populations. For example, lethal effects, diminished health, prey and

[111] Haney JC, Geiger HJ, Short JW (2014) Acute bird mortality from the Deepwater Horizon MC 252 oil spill. II. Carcass sampling and exposure probability estimates for coastal Gulf of Mexico. Mar Ecol Prog Ser doi: 10.3354/meps10839
[112] Schrope M (2014, May 5) Still Counting Gulf Spill's Dead Birds. New York Times. The New York Times Company, New York.
[113] Montevecchi W, Fifield D, Burke C, Garthe S, Hedd A, Rail JF, Robertson G (2012) Tracking long-distance migration to assess marine pollution impact. Biol Lett 8:218-221

habitat switching, diminished plumage quality, or delayed migration might affect migratory shorebird populations in the upland prairie and subarctic regions far removed from the Gulf.[114]

Significant evidence indicates actual harm to bottlenose dolphin populations due to exposure to Macondo well oil in combination with other stresses. Most of the carcasses of marine mammals collected during and after the Macondo well blowout were bottlenose dolphins (*Tursiops truncates*). Marine mammal stranding data indicate a prolonged unusual mortality event (UME) for bottlenose dolphins has been occurring from around the time of and subsequent to the blowout. The frequency of strandings of dolphin dead or in stress has been more than four times the long-term average. The stranding of fetal or new-born (perinatal) and juvenile dolphins that are in poor condition due to depleted food resources or disease during the four months beginning with January 2011 is particularly noteworthy. This was the first calving season after the Macondo well blowout as well as a very cold winter in 2010.[115]

During 2011, the health of bottlenose dolphins living in Barataria Bay, where they had been breathing oil fumes at the water's surface, was compared to a well-studied population residing in Sarasota Bay, Florida, well removed from stranded oil from the Macondo well blowout.[116] As opposed to reliance on autopsies of dead animals, dolphins were captured, examined and released. Vital signs were observed; blood, hormone and blubber specimens were collected; and lung health was tested on the captured dolphins. Barataria Bay dolphins showed evidence of insufficient adrenocortical hormones (hypoadrenocorticism, known as Addison's disease when it occurs in dogs and horses), consistent with adrenal toxicity that occurs in laboratory mammals exposed to oil. They were five times more likely to have moderate to severe lung disease as diagnosed by ultrasound than those in Sarasota Bay. Of the 29 dolphins evaluated from Barataria Bay, 47% were given a guarded or worse prognosis and 17% were considered poor or grave and not expected to survive. Disease conditions in Barataria Bay dolphins that could affect survival and reproduction were also more prevalent and severe; some of these conditions were uncommon in dolphins but consistent with petroleum hydrocarbon toxicity.

As was the case with articles that purported to demonstrate effects on Gulf killifish, deepwater corals, and lingering sublethal toxicity on the West Florida Shelf, the Barataria Bay dolphin study was criticized in the journal in which it was published by a scientific consultant to the oil industry. Although a number of issues were raised, the principal criticism was the lack of a dose-response relationship conventionally used in toxicology.[117] In their reply to this response, the investigators

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[114] Henkel JR, Sigel BJ, Taylor CM (2012) Large-scale impacts of the Deepwater Horizon oil spill: Can local disturbance affect distant ecosystems through migratory shorebirds? Bioscience 62:676-685

[115] Carmichael RH, Graham WM, Aven A, Worthy G, Howden S (2012) Were multiple stressors a 'perfect storm' for northern Gulf of Mexico bottlenose dolphins (*Tursiops truncatus*) in 2011? PLoS One 7:e41155

[116] Schwacke LH, Smith CR, Townsend FI, Wells RS, Hart LB, Balmer BC, Collier TK, De Guise S, Fry MM, Guillette LJ, Lamb SV, Lane SM, Mcfee WE, Place NJ, Turnlin MC, Ylitalo GM, Zolman ES, Rowles TK (2014) Health of common bottlenose dolphins (*Tursiops truncatus*) in Barataria Bay, Louisiana, following the Deepwater Horizon oil spill. Environ Sci Technol 48:93-103

[117] Jacobs LA (2014) Comment on health of common bottlenose dolphins (*Tursiops truncatus*) in Barataria Bay, Louisiana, following the Deepwater Horizon oil spill. Environ Sci Technol 48:4207-4208

pointed out that experimental exposure required to develop such a relationship is constrained by logistics and ethics. Further, they argued that a correlation study such as theirs can provide strong evidence for a causal relationship when findings are consistent with other experiments and where plausible alternative hypotheses are ruled out.[118]

Results thus far are insufficient to assess the potential for harm for whales and dolphins occurring offshore. In addition to coastal dolphin populations, sperm, Bryde's, pygmy sperm, and beaked whales and other dolphin species reside in the deepwater and continental shelf regions of the northern Gulf of Mexico near the Macondo wellhead. Exposure to oil slicks while these marine mammals are at the ocean's surface, and some of the whales dive and feed deeply where they could encounter deep sea hydrocarbon plumes or consume contaminated prey. While some acoustic recordings suggest that sperm whales were avoiding the area around the Macondo well,[119] evidence is insufficient to conclude either that there was a potential for harm or that harm was highly unlikely.

6.6 Fisheries

Actual or potential harm can be considered from the perspective of both the effects on populations of fish and shellfish themselves and the impacts on their fisheries, that is the enterprises engaged in raising or harvesting, processing and selling the commodities. In 2009, the year before the blowout, the seafood industry generated over $17 billion in sales in the Gulf states and expenditures on recreational fishing trips and durable equipment in the Gulf region totaled over $10 billion.[120]

The ultimate effects of the Macondo well blowout on fish and shellfish stocks are inherently difficult to assess. Oil pollution does not usually produce large fish kills, but affects populations through adverse effects on survivability, reproduction, prey, and habitats. The published results reviewed in this report on gene expression and embryo development of Gulf killifish; heart functions in larval tunas and amberjack; and swimming speed in young mahi-mahi, and the association of lesions in bottom-dwelling fish with elevated PAH levels in their liver support a conclusion of possible harm to fish populations.

The economic impacts on Gulf of Mexico fisheries were substantial and are continuing. The evidence of effects on the fisheries of the Gulf, however, was not so subtle. The closures of Federal and state waters to commercial fishing reduced the value of seafood landings by at least $247

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[118] Schwacke LH, Smith CR, Townsend FI, Wells RS, Hart LB, Balmer BC, Collier TK, De Guise S, Fry MM, Guillette LJ, Lamb SV, Lane SM, Mcfee WE, Place NJ, Tumlin MC, Ylitalo GM, Zolman ES, Rowles TK (2014) Response to comment on health of common bottlenose dolphins (*Tursiops truncatus*) in Barataria Bay, Louisiana following the Deepwater Horizon oil spill. Environ Sci Technol 48:4209-4211

[119] Ackleh AS, Ioup GE, Ioup JW, Ma BL, Newcomb JJ, Pal N, Sidorovskaia NA, Tiemann C (2012) Assessing the Deepwater Horizon oil spill impact on marine mammal population through acoustics: Endangered sperm whales. J Acoust Soc Am 131:2306-2314

[120] National Marine Fisheries Service (2010) Fisheries Economics of the United States, 2009. U.S. Dept. Commerce NOAA Tech. Memo. NMFS-F/SPO-118, 179p., https://www.st.nmfs.noaa.gov/st5/publication/index.html

million[121] and the subsequent public aversion to Gulf seafood exacerbated and extended this economic effect despite an unprecedented level of monitoring of seafood that showed, with very few exceptions, that the seafood was safe to consume.[122] One attempt to model the longer-term impacts on commercial and recreational fisheries and mariculture suggests that the Macondo well blowout could result over a seven-year period in losses in total revenue of $3.7 billion, with a total economic impact of $ 8.7 billion.[123]

7. CONCLUSIONS

7.1. Status and Evolution of Scientific Understanding

A surprising number of very competent and informative articles describing the consequences of the Macondo well blowout appeared in the scientific literature within the first year. Several articles describing the physical, chemical and biological dynamics of the deepwater plume were published literally days after the well was capped. Despite the current paucity of residual oil to study, important results continue to be published as a result of time required to analyze data, monitoring of long-term fate and effects, or conducting follow-up experiments and modeling. Several of the scientific articles that form the basis of some of my conclusions were just published in 2014 and many more manuscripts are currently in the hands of peer reviewers and journal editors. Vast amounts of data have been and are still being collected as part of the Natural Resources Damage Assessment. Because of the ongoing legal process substantial portions of the analyses of these results have been regarded as confidential and remain unpublished in the peer-reviewed literature. In addition, an extensive volume of research on the consequences of the Macondo well blowout is ongoing under the Gulf of Mexico Research Initiative (GoMRI) funded by BP.

While there currently is a sizeable literature on which to draw, it is clear that much more information about and understanding of the environmental consequences of the blowout are still to come. There will be surprises, but also clearer and more confident understanding will emerge over the next few years, just as it took many years to emerge from studies of the Exxon Valdez oil spill. NRDA results will eventually become available and GoMRI will invest more of its resources in integrative interpretation of its results rather than basic data collection, as in fact it is beginning to do so now. This scientific evolution will better resolve: (a) the many uncertainties to which I have alluded throughout this assessment, (b) the significance of observed responses at the levels of populations, ecosystems and the services these ecosystems provide to humans;[124] and (c) long-term

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[121] McCrea-Strub A, Kleisner K, Sumaila UR, Swartz W, Watson R, Zeller D, Pauly D (2011) Potential Impact of the Deepwater Horizon Oil Spill on Commercial Fisheries in the Gulf of Mexico. Fisheries 36:332-336

[122] Ylitalo GM, Krahn MM, Dickhoff WW, Stein JE, Walker CC, Lassitter CL, Garrett ES, Desfosse LL, Mitchell KM, Noble BT, Wilson S, Beck NB, Benner RA, Koufopoulos PN, Dickey RW (2012) Federal seafood safety response to the Deepwater Horizon oil spill. Proc Natl Acad Sci USA 109:20274-20279

[123] Sumaila UR, Cisneros-Montemayor AM, Dyck A, Huang L, Cheung W, Jacquet J, Kleisner K, Lam V, McCrea-Strub A, Swartz W, Watson R, Zeller D, Pauly D (2012) Impact of the Deepwater Horizon well blowout on the economics of US Gulf fisheries. Can J Fish Aquat Sci 69:499-510

[124] National Research Council (2013) An Ecosystem Services Approach to Assessing the Impacts of the Deepwater Horizon Oil Spill in the Gulf of Mexico. National Academies Press, Washington DC

effects and the time course of ecosystem recovery. For these reasons is premature to be completely definitive about harm, whether actual or potential, at this time. Fortunately, through the NRDA, GoMRI and other programs there are unprecedented opportunities to better quantify the consequences, scale and duration of harm resulting from the Macondo well blowout over the next few years.

7.2. Real and Potential Harm

As stated in Section 2.4 I have used "actual harm" to describe a demonstrated effect that altered the normal functions and populations in an ecosystem. I used "potential harm" when evidence suggests that there might be actual harm but does not yet conclusively demonstrate it.

In this cautious sense, I conclude that substantial actual harm was realized among: (a) planktonic and floating seaweed communities exposed to the deep sea hydrocarbon plume or surface oil slicks; (b) biota inhabiting the deep seabed in the vicinity of the Macondo well, including cold-water communities, which received oily deposits; (c) moderately to heavily oiled coastal marshes and mangroves and animals closely associated with them, including insects, crabs, shrimp and fish; and (d) birds, sea turtles and dolphins exposed to oil slicks. There was potential harm to: (a) fishes living near the seabed on the outer continental shelf and continental slope where hydrocarbons contaminated sediments, (b) open ocean fishes such as tunas and mahi-mahi with larvae that develop near the sea surface; (c) biota inhabiting the seabed on the continental shelf in the vicinity of substantial floating oil; and (d) oyster stocks in areas affected by oil and related response actions.

It is humbling to take note of observations in the surprises and enigmas that materialized as the effects of the Exxon Valdez oil spill played out, for example the crash in Prince William Sound herring populations four years after the spill.[125] So, even my qualitative conclusions should be accompanied by the caveat that for the Macondo well blowout, as well, there may yet be other effects that are uncovered as effects ripple through ecosystems

For the reasons discussed in the context of the evolution of scientific understanding, it is still difficult to quantify the magnitude of harm other than to note that multiple components of the ecosystems were harmed over large areas, some ecosystems remain injured, and recovery of others is not yet well documented. Early predictions by members of the public and even some scientists that there would be wholesale "collapse" of ecosystems were naïve to the professional understanding of the effects of oil spills and offshore blowouts and to the scale and dynamics of the Gulf of Mexico. In that more realistic context, the harm caused by the large and sustained release of hydrocarbons as a result of the Macondo well blowout must be regarded as profound and extensive, particularly in comparison with previous offshore blowouts.

7.3. Harm in the Context of Multiple Stressors

[125] Rice, S.D. (2014) Toxicological Impact of the MC252 Blowout, Oil Spill, and Response. Expert Report submitted on behalf of the United States. U.S. v. BP Exploration & Production et al., 16.

The harm caused by the Macondo well blowout must also be evaluated in the context of the multiple stresses confronting marine organisms and their ecosystems. Many of these other stressors are also the result of human activities, including: (a) introduction of pollutants that are toxic or stimulate excess production, causing algal blooms and dead zones; (b) destruction of wetlands and other habitats; (e) fishing pressures that affect populations of target and non-target species, alter food webs, and disturb bottom habitats; (f) introduction of invasive species; and (e) global warming. All of these were major factors in the diminution of ecosystem services of the northern Gulf of Mexico even before the Macondo well blowout.

It is seldom the case that there is only one exclusive factor affecting ecosystems or organisms. Factors may interact, one factor contributing to the sensitivity to others. Understanding the interaction of multiple stresses is important at every organizational level. Oil pollutants interact with natural and other human-induced stressors to compound toxicological effects at the molecular level such as demonstrated in the Gulf killifish study.[126] Interactions of sublethal effects on larvae and juveniles of tuna or mahi-mahi interact with the physical and biological processes that determine year-class recruitment at the population level. As discussed in Section 6.3 the erosion of marsh edges due to heavy oiling compounds the wetland losses due to sea-level rise and other factors.[127] Because an extraneous factor has a dominant influence does not necessarily mean that a stress induced by the blowout is insignificant, rather it may be compounding.

7.4. Expansive Scale of Real and Potential Harm

The geographic scale of documented impacts of the Macondo well blowout is among the most expansive ever documented for ocean oil spills and blowouts. Floating oil extended over 68,000 square miles of sea surface at one time or another during the summer of 2010 and stranded on at least 1,138 miles of shoreline, including 495 miles of wetland shores. Documented impacts on bottom-dwelling communities around the wellhead extended over at least 57 square miles of deep ocean floor and the fall out of biodeposited oil likely extended over an even larger area.

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[126] Whitehead A (2013) Interactions between oil-spill pollutants and natural stressors can compound ecotoxicological effects. Integr Comp Biol 53:635-647

[127] Mendelssohn IA, Andersen GL, Baltz DM, Caffey RH, Carman KR, Fleeger JW, Joye SB, Lin Q, Maltby E, Overton EB, Rozas LP (2012) Oil impacts on coastal wetlands: implications for the Mississippi river delta ecosystem after the Deepwater Horizon oil spill. BioScience 62:562-574

7.5. Time Scale of Recovery and Resilience of Gulf Ecosystems

The time required for Gulf ecosystems to recover from a hydrocarbon blowout depends primarily on (a) the degree to which hydrocarbon contamination remains and (b) biological processes regulating the reestablishment of populations. The reasons that certain components of the Prince William Sound ecosystem have recovered very slowly from the Exxon Valdez oil spill were either because of lingering, undegraded contamination where oil had seeped into poorly oxygenated sediments of the intertidal zone or because of inherent limitations in population recovery, such as with pods of killer whales.[128] Some parts of Gulf of Mexico ecosystems, such as heavily oiled marshes, the deep seabed around the Macondo well, and beaches with tar mats, remain contaminated four years after the blowout. It seems likely that some years more will be required before hydrocarbon contamination returns to background levels. The time required for recovery of affected populations also varies greatly. Plankton populations no doubt recovered within months if not sooner, reseeded by extensive surrounding reservoirs of unaffected plankton. However, if larvae of blue fin tuna were significantly diminished, the effects on the year-class structure of the whole Western Atlantic population would be affected, with multi-year consequences. Local populations of affected bottlenose dolphins or sea turtles, which are both broadly migratory and endangered, could be set back for years. We do not really know how long a 400-year old deepwater coral colony will take to recover. Moreover, where marsh soils were eroded away after being heavily oiled, cordgrass and needlerush may never be able to reclaim the real estate that they lost.

While any claim that the Gulf of Mexico has fully recovered is certainly an overstatement, it is also clear that its ecosystems are resilient. These ecosystems accommodate the dynamic ocean with energetic rings spun off by the Loop Current, hurricanes, cold fronts, river floods, sediment resuspension by waves and currents, natural oil seeps and toxic algal blooms. At the same time the resilience of the ecosystems is itself compromised by multiple human stresses: the broken Mississippi Delta, agricultural pollution causing dead zones and more toxic algal blooms, seas that are warming, acidifying and rising, bottom trawling, overfishing, the vast steel oil and gas infrastructure, and introduced invasive species such as lionfish. Prudent stewardship can no longer rely on the resilience of ecosystems to clean up our mistakes.

INFORMATION REQUIRED BY THE FEDERAL RULES OF CIVIL PROCEDURE

1. This report contains my opinions, conclusions, and reasons therefore.

2. A general statement of my qualifications is contained in the Expert's Background section, page 4. A supplemental description of my qualifications is included in my attached CV, Appendix A.

[128] 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

3. The articles I have authored in the last 10 years are included in my attached CV, Appendix A.

4. My compensation for the preparation of this report and any testimony as an expert witness at trial or deposition is as follows: $260 per hour or $350 for deposition or trial testimony.

5. I have previously testified as an expert witness in the case of *Louisiana v. Lujan*, 777 F. Supp. 486, 489 (E.D. La. 1991).

6. The facts and data I considered in forming my opinions are listed in Appendix B. The opinions expressed in this report are my own and are based on the facts and data available to me at the time I wrote this report. Should additional relevant information become available, I reserve the right to supplement the discussion and findings in this report.

APPENDIX A

DONALD F. BOESCH

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Website: www.umces.edu/people/president

Birth: [redacted]

Education: B.S., 1967, Biology, Tulane University
Ph.D., 1971, Marine Science, College of William and Mary

Present Positions: President and Professor of Marine Sciences, 1990-present, University of Maryland Center for Environmental Science
Vice Chancellor for Environmental Sustainability, 2008-present, University System of Maryland

Previous Positions: Interim Vice Chancellor for Academic Affairs, University System of Maryland, 2002-2003
Executive Director, Louisiana Universities Marine Consortium; Professor of Marine Science, Louisiana State University, Baton Rouge; 1980-90
Associate Marine Scientist and Assistant Professor, 1972-77; Senior Marine Scientist and Associate Professor, 1977-80; Virginia Institute of Marine Science, College of William and Mary
Fulbright-Hays Postdoctoral Fellow, University of Queensland, 1971-72.

Honors and Awards:

Beta Beta Beta (biological honorary society); Federal Water Pollution Control Administration (now U.S. EPA) Predoctoral Fellow; Fulbright-Hays Postdoctoral Fellow; Sigma Xi; National Conference on Ecosystem Restoration Award for Lifetime Leadership in Ecosystem Restoration; Maryland Public Television-Outdoors Maryland Award for Stewardship of the Environment; Maryland-Asia Environmental Partnership Leadership Award; National Associate of the National Research Council

Membership in Professional Societies:

American Association for the Advancement of Science; American Geophysical Union; American Society of Limnology and Oceanography; Ecological Society of America; Estuarine Research Federation (Vice President, 1985-87, President, 1987-89)

Research Interests:

Environmental and natural resource management: application of science, adaptive ecosystem management and restoration, oil and gas development, habitat modification, fisheries
Biological oceanography: benthos, communities, ecosystems, recruitment processes
Estuaries: ecology, evolution, physical processes, climate change
Continental shelves: oceanography, ecology
Sedimentology: effects of organisms on sediment dynamics and geochemistry
Marine pollution: eutrophication, oil, dredged material
Global climate change: impacts and adaptation

Appointments to Advisory and Policy Boards *(Active engagements in italics)*:

U.S. Government Agencies

Department of the Interior: Scientific Committee, OCS Advisory Board, 1979-82, 1984-1987, Chair, 1984-85; Florida Bay Scientific Review Panel, Chair, 1993; Florida Bay Interagency Science Program: Science Oversight Panel, Chair, 1995-1998.

National Science Foundation: Biological Oceanography Panel, 1983-1984; Advisory Committee on Ocean Sciences, 1984-1989, Vice-Chair, 1987-88, Chair, 1988-89.

Environmental Protection Agency: Science Advisory Board, 1990-1994; Gulf of Mexico Program, Environmental Protection Agency, Technical Steering Committee, 1988-1990; Chesapeake Bay Program, Scientific and Technical Advisory Committee 1990-2010, National Advisory Council on Environmental Protection and Technology, 1993-1997.

National Oceanic and Atmospheric Administration: Panel on the Coastal Ocean, 1990-91, Co-Chair, 1990-91; NOAA-University Partnership Action Committee, 1996-1998.

U.S. Army Corps of Engineers: Louisiana Coastal Area Ecosystem Restoration Program, National Technical Review Committee, 2002-2005.

U.S. Geological Survey: Louisiana Coastal Area Ecosystem Restoration Program, Science Board, Chair, 2006-2009.

U.S. Global Change Research Program: Co-chair, Coastal Zone Sector Panel, U.S. National Assessment: The Potential Consequences of Climate Variability and Change, 1998-2000; Committee to Prepare a Unified Synthesis Product, 2008-2009; Review Editor, Coastal Zone Development and Ecosystems, National Climate Assessment, 2013.

U.S. Commission on Ocean Policy, Scientific Advisory Panel, 2001-2004.

U.S. Navy Office of Naval Research: Ocean Research Advisory Panel, 2010-2013.

Executive Office of the President: National Commission on BP Deepwater Horizon Oil Spill and Offshore Drilling, 2010-2011.

National Research Council

Marine Board, 1983-89, Executive Committee, 1984-85; Panel on Effects of Drilling Fluids and Cuttings in the Marine Environment, 1981-83; Committee on Assessment of Marine Environmental Monitoring Systems, Chair, 1987-89.

Ocean Studies Board, 1989-1995, 2007-2012; Chair, 2009-2012; Committee on the Coastal Ocean, Chair, 1990-95.

Water Science and Technology Board: Committee to Assess the Army Corps of Engineers Methods of Analysis and Peer Review for Water Resources Project Planning, Chair, Panel on Adaptive Management for Resource Stewardship, 2001-2003; Committee on Independent Scientific Review of Everglades Restoration Progress, 2004-2008.

Board on Life Sciences: Committee on Ecological Impacts of Climate Change, 2008.

Board on Atmospheric Science and Climate: Committee on America's Climate Choices, 2008-2011.

NAS Gulf of Mexico Research Program, *Advisory Group, 2013-2014.*

State and University

Louisiana Board of Regents Research and Development Program: Louisiana Stimulus for Excellence in Research (LaSER), Project Director, 1985-1990; Louisiana Education Quality Support Fund, Planning Committee, Vice-Chair, 1987-1990.

University System of Maryland Foundation: *Board of Directors (ex officio), 1990-present.*

Maryland Governor's Office: *Governor's Chesapeake Bay Cabinet, 1990-present; 2010 Trust Fund, Scientific Advisory Panel, Chair, 2008-present.*

Maryland Department of the Environment: Maryland Environment 2000, Steering Committee, 1994-1996.

Maryland Department of Natural Resources: Maryland Oyster Roundtable, 1993-; Maryland Coastal Bays Program, Implementation Committee, Scientific and Technical Advisory Committee, Chair, 1996-2001; Harmful Algal Outbreak Technical Advisory Committee, Chair, 1997-2002; *Maryland Oyster Advisory Commission, 2007-present.*

Maryland Commission on Climate Change: *Chair of Scientific and Technical Working Group, 2007-present.*

Non-Governmental Organizations

Chesapeake Research Consortium, Inc.: *Board of Directors, 1991-present.*

Chesapeake Bay Foundation: Board of Trustees, 1991-2002, 2004-2013, *Honorary Trustee, 2013-present.*

Alliance for the Chesapeake Bay: Board of Directors, 1992-2008, President, 1994-96.

Town Creek Foundation: *Board of Directors, 2007-present.*

Consortium for Ocean Leadership: *Board of Trustees*, 2007-2008, *2009-present.*

Council on Ocean Affairs: Steering Committee, 1989-93, Chair, 1989-90.

Consortium for Ocean Research and Education: Board of Governors, 1993-2007; Vice-Chair, 1998-2000; International Scientific Steering Committee, Census of Marine Life, 1999-2004.

National Association of State Universities and Land Grant Colleges: Commission on Food, Natural Resources and Environment, 1996-2002.

Council on Ocean Law: Board of Directors, 1992-2005.

Seaweb, Science Spokesteam, 1997-2000

Communication Partnership for Science and the Sea (COMPASS), Group of Scientific Experts, 1999-2004; Scientific Advisor, 2005-2009; *Principal, 2009-present.*

America's Wetland Foundation, Big River Works, *Steering Committee, 2012-present.*

Environmental Defense Fund, Changing Course: Navigating the Future of the Lower Mississippi River Delta, *Leadership Team, 2012-present.*

Joint Ocean Commission Initiative, *Leadership Council, 2013-present.*

International

Programa de Ecología, Pesquerías y Oceanographía del Golfo de México (EPOMEX), Universidad Autónoma de Campeche: Scientific Council, 1992-1997.

European Commission, *BONUS for Baltic Sea Science Advisory Panel, 2004-present.*

Swedish Environmental Protection Agency, Expert Panel on Marine Eutrophication, 2005-2006, 2008.

The Ecologic Institute, Berlin, *RADOST: Regional Adaptation Strategies for the German Baltic Sea Coast, Advisory Board, 2010-present.*

Frontiers in Global Change and the Future Ocean, *Review Editor, 2014-present*

Publications:

Boesch, D. F. 1971. On the occurrence of *Pinnixa lunzi* (Decapoda: Pinnotheridae) off Virginia. *Crustaceana* 20:219-220.

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APPENDIX B

Appendix B to Expert Report of Donald F. Boesch
Consideration Materials
(Documents Cited in Report are Consideration Materials even if Not Listed Below)

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Trial Transcript (Oct. 15, 2013 am)
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(Documents Cited in Report are Consideration Materials even if Not Listed Below)

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Consideration Materials
(Documents Cited in Report are Consideration Materials even if Not Listed Below)

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Consideration Materials
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Consideration Materials
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