4.4 Water Column

What Is in This Section?

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- **Conclusions and Key Aspects of the Injury for Restoration Planning (Section 4.4.6):** What are the Trustees' conclusions about injury to water column organisms, ecosystem effects, and restoration considerations?
- **References (Section 4.4.7)**

Executive Summary

The DWH incident resulted in a large, continuous release of oil at a depth of 1,500 meters in the northern Gulf of Mexico over a period of 87 days before the well was capped. The spill exposed many different and highly diverse biological communities throughout the water column to oil. Prior to this spill, many of the biota in this area had not been well studied. After the spill began, the Trustees conducted a large, sustained, and multifaceted oceanographic field program, including more than 40 cooperative studies with BP that involved multiple oceanographic research vessels, remotely operated underwater vehicles, aircraft, satellite resources, and other specialized equipment. This effort produced a large inventory of physical, biological, and chemical data.

However, because the impacted area is vast and empirical data were ephemeral, the Trustees could not fully characterize the contamination in space and time. As such, the Trustees quantified injury to water column biota by combining available empirical data with several different modeling analyses.

The area of oil observed floating on the ocean surface for the duration of the spill was quantified using remote sensing imagery. The volume of water in the subsurface mixed zone was quantified using empirical chemistry data collected under the footprint of the floating oil. The number of biological organisms killed due to direct exposure to the slick or lethal concentrations of polycyclic aromatic hydrocarbons (PAHs) in the upper water column was calculated using data synthesized from Natural

Resource Damage Assessment (NRDA)-specific field studies, historical collections, NRDA toxicity testing studies, and the published literature. The spill resulted in a surface slick that covered a cumulative area of at least 112,100 square kilometers (43,300 square miles) for 113 days in 2010. Via mixing due to winds and waves, the average daily volume of water affected by surface oil slicks was 57 billion cubic meters (15 trillion gallons). This occurred in an area of high species diversity during a time of year (spring and summer) when seasonal productivity peaks in the northern Gulf of Mexico. The Trustees quantified the direct kill and foregone production of fish and invertebrates exposed to DWH oil in the surface slick and the subsurface mixed zone. The exposure resulted in the death of between 2 and 5 trillion fish larvae and between 37 and 68 trillion planktonic invertebrates.

The Trustees used a combination of modeling and empirical data to quantify the volume of contaminated subsurface water in the cone of rising oil, the volume of contaminated subsurface water in the deep water plume, the amount of small oil droplets found in subsurface "clouds," and the amount of dissolved contaminants. The NRDA sampling in the deep water highlights the diversity and abundance of animals exposed to oil in the deep pelagic waters of the Gulf of Mexico. The Trustees quantified the direct kill of fish and invertebrates exposed to DWH oil both in the rising cone of oil and in the deep water plume. They also investigated foregone production for a critical subset of these species. The exposure resulted in the death of between 86 million and 26 billion fish larvae and between 10 million and 7 billion planktonic invertebrates.

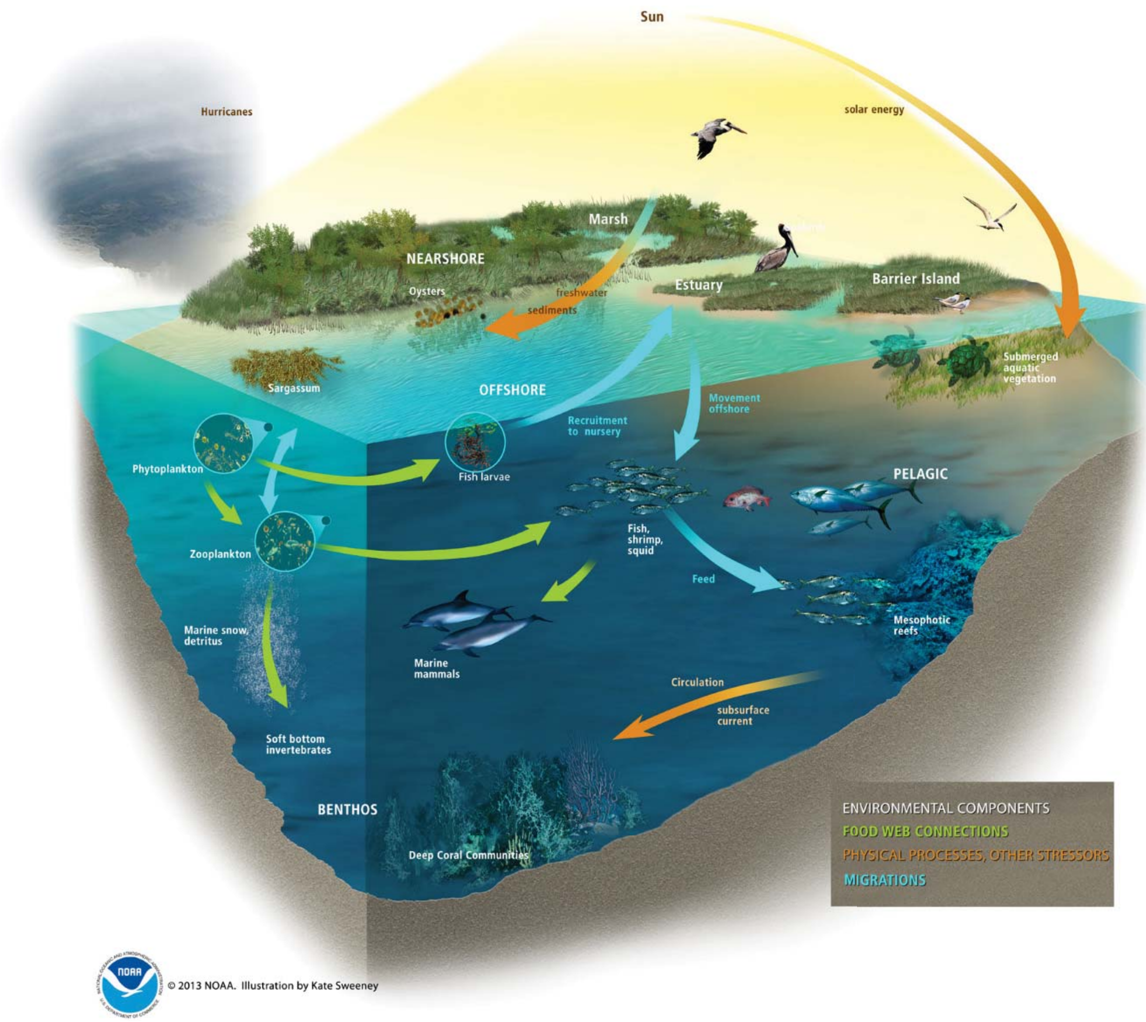
The Trustees also quantified injury to *Sargassum,* a brown marine algae that creates essential habitat for invertebrates, fish, birds, and sea turtles. The Trustees quantified both the lost area of *Sargassum* that resulted from direct oiling and the foregone growth that resulted from this exposure. Heavy oil (greater than 5 percent coverage) affected 23 percent of the *Sargassum* (873 to 1,749 square kilometers) in the northern Gulf of Mexico, resulting in a range of lost *Sargassum* area from foregone growth between 4,524 and 9,392 square kilometers. The Trustees did not quantify lethal and sublethal effects to *Sargassum*-dependent fish and decapods, but include in this section a qualitative discussion about the effects of habitat loss and direct oil exposure to these animals.

4.4.1 Introduction and Importance of the Resource

The Gulf of Mexico waters support a wide variety of organisms, including plankton, more than a thousand known fish species at different life stages (Felder & Camp 2009), mobile invertebrates (such as shrimp, crabs, and squid), sea turtles, seabirds, and marine mammals. These organisms, among others, play important ecological roles. For instance, they serve as prey or predators in the food web, and they cycle and transport nutrients both horizontally (between nearshore and offshore areas) and vertically (between the surface and deep water). Many fish and crustaceans support robust commercial and recreational fisheries. *Sargassum* is an important offshore habitat at the surface for juvenile fish and turtles, providing both shelter and food. *Sargassum* is a key habitat of the ecosystem in the northern Gulf of Mexico, providing the only naturally occurring floating structure in an otherwise featureless open ocean. Figure 4.4-1 illustrates biological communities included in the water column section and indicates key ecosystem processes; Figure 4.4-2 illustrates types of fauna that depend on and use *Sargassum,* including fish, sea turtles, birds, and marine mammals.

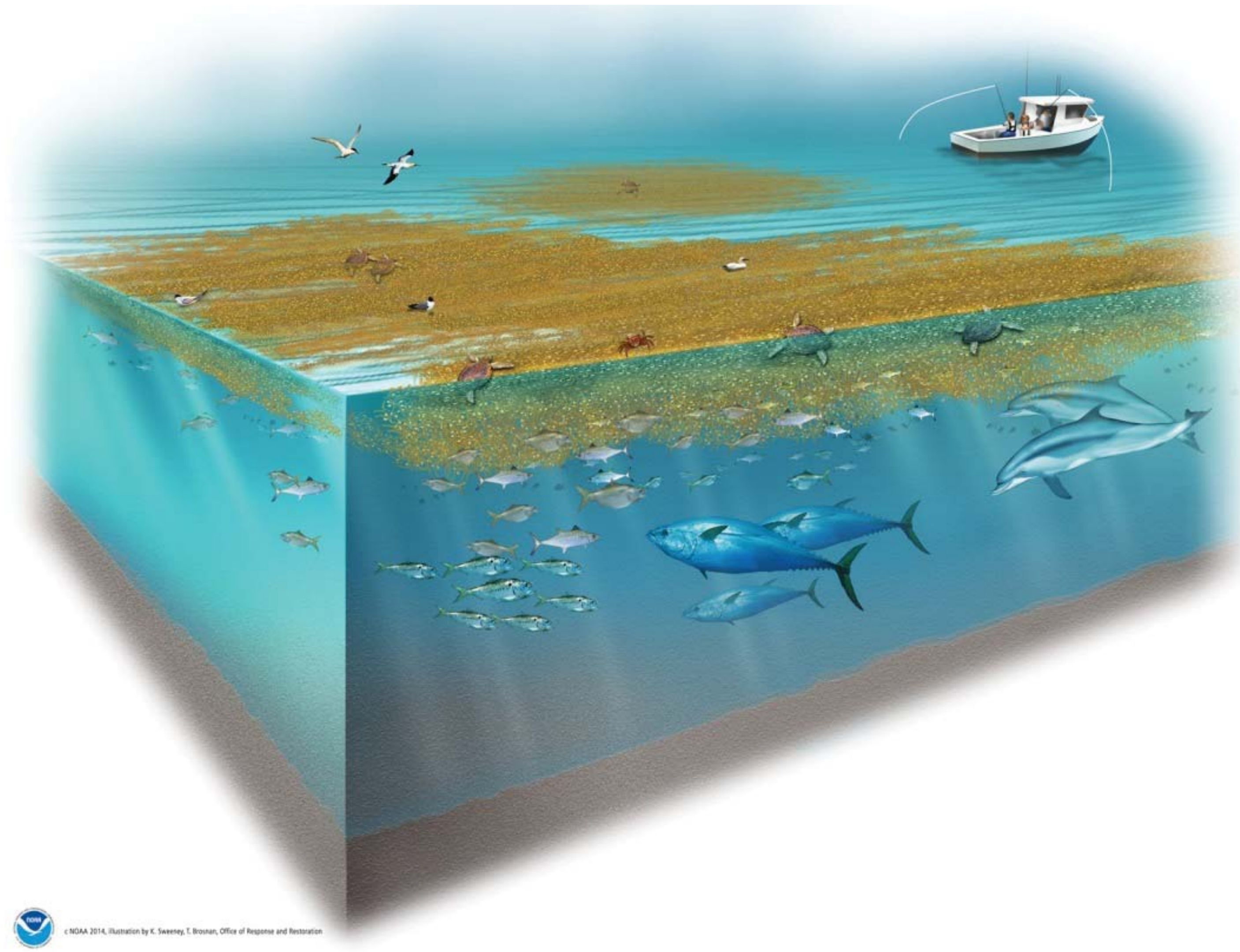
Following the DWH blowout, the oil and dispersants that spread throughout the water column in the deep sea, offshore regions, and nearshore regions impacted these productive and diverse environments (Section 4.2, Natural Resources Exposure). Animals were bathed in a fluid environment that contained surface oil, oil droplets, dissolved oil, dispersants, and elevated concentrations of PAHs. These organisms may have ingested contaminated water, food, and particles; had contaminated water flow over gills; and come into direct contact with extensive oil slicks. Physical processes, such as convergent currents and fronts that play a role in transporting, retaining, and concentrating organisms and *Sargassum*, are the same processes that act to concentrate oil, thus increasing the exposure of organisms to oil. Sunlight, essential for fueling photosynthesis that results in highly productive surface waters, also acts synergistically with PAHs to increase oil toxicity (Section 4.3, Toxicity).

This section addresses injuries to water column resources during and after the spill. The working definition of "water column" here includes virtually everything aquatic or dependent on aquatic systems extending from the shoreline out to deep waters. Not included are sediment-associated benthic communities, birds, sea turtles, and marine mammals, which are addressed in other sections of this document.



Source: *Kate Sweeney for NOAA.*

Figure 4.4-1. Illustration depicting the biological communities included in this section and indicating key ecosystem processes. Depicted here are the various areas of the water column, including estuary and offshore/oceanic areas. Green arrows indicate foodweb connections, blue arrows show migrations of biota from one zone to another, and orange arrows show physical processes that influence the biological communities.



Source: *Kate Sweeney for NOAA.*

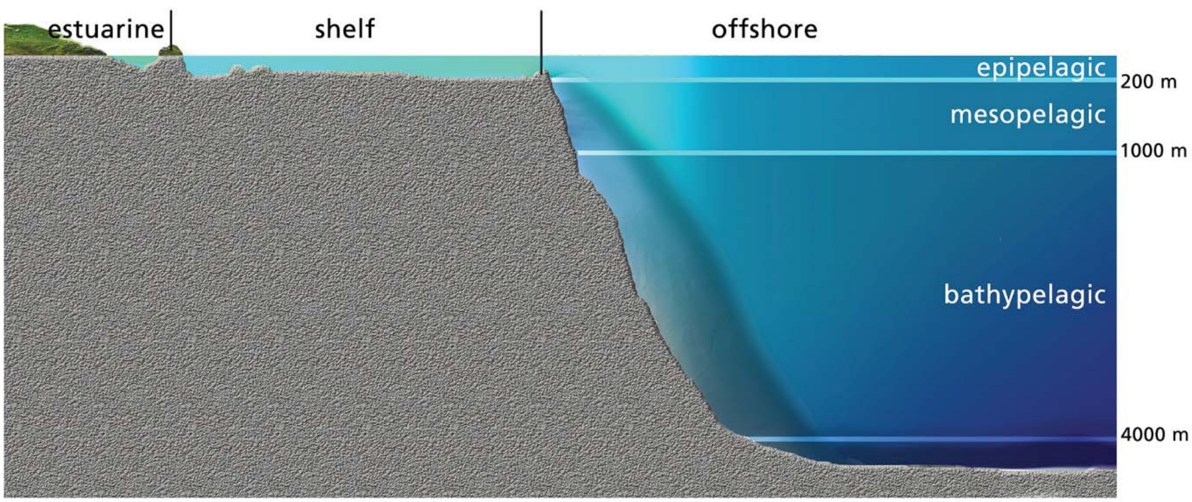
Figure 4.4-2. Illustration of *Sargassum* and associated fauna, including fish, sea turtles, birds, and marine mammals. *Sargassum* is a brown algae that forms a unique and highly productive floating ecosystem on the surface of the open ocean.

4.4.1.1 Water Column Areas and Zones

The northern Gulf of Mexico water column is composed of various habitats, ranging from shallow estuarine waters to dark, deep water environments. Many physical and chemical features (or characteristics) govern these habitats. Examples include light; depth; temperature; pressure; salinity; currents; freshwater inputs; and transport of organic matter, nutrients, and sediments. Horizontal and vertical zones of the water column are outlined below and illustrated in Figure 4.4-3.

Horizontally, the water column can be divided into three main areas: 1) the ***estuarine area*** extending from the barrier islands inward; 2) the ***shelf/neritic area*** over the continental shelf, extending from the barrier islands to the continental shelf break; and 3) the ***offshore/oceanic area*** extending from the shelf break outward.

Vertically, the water column is governed by light, depth, temperature, and pressure. The three main depth zones are: 1) the ***epipelagic zone***, in the upper 200 meters of the water column, where there is enough light for photosynthesis to occur; 2) the ***mesopelagic zone*** from the bottom of the epipelagic zone to approximately 1,000 meters beneath the ocean surface, where some light penetrates, but not enough to fuel photosynthesis; and 3) the ***bathypelagic zone*** from approximately 1,000 to 4,000 meters in depth. Without any sunlight, the bathypelagic zone is dark and cold and is under high pressure due to its depth.



Source: *Kate Sweeney for NOAA.*

Figure 4.4-3. The horizontal and vertical zones of the water column in the northern Gulf of Mexico. Horizontally, the water column can be described in three main areas: the estuarine area (barrier islands inward), the shelf/neritic area (barrier islands to shelf break), and the offshore/oceanic area (shelf break outward). Vertically, the water column includes three main depth zones: the epipelagic zone (0–200 meters beneath the ocean surface), the mesopelagic zone (200–1,000 meters deep), and the bathypelagic zone (1,000–4,000 meters deep).

4.4.1.2 Water Column Species

The water column in the northern Gulf of Mexico provides a large and expansive habitat for a diverse community of species, all of which make up an interconnected and complex food web (Figure 4.4-4;

Chapter 3, Ecosystem Setting). At the bottom of the food web are phytoplankton and zooplankton, which are important food sources for many species of fish and crustaceans (i.e., planktivores). In turn, these planktivores are food for larger predatory species such as tuna and sharks. Table 4.4-1 lists different living marine resources found in the water column, from microscopic bacteria to large predatory fish. The table also describes these resources' importance in the ecosystem and their connection to different Gulf habitats.

Table 4.4-1. Description of selected water column resource groups found in the Gulf of Mexico and their importance to the Gulf ecosystem.

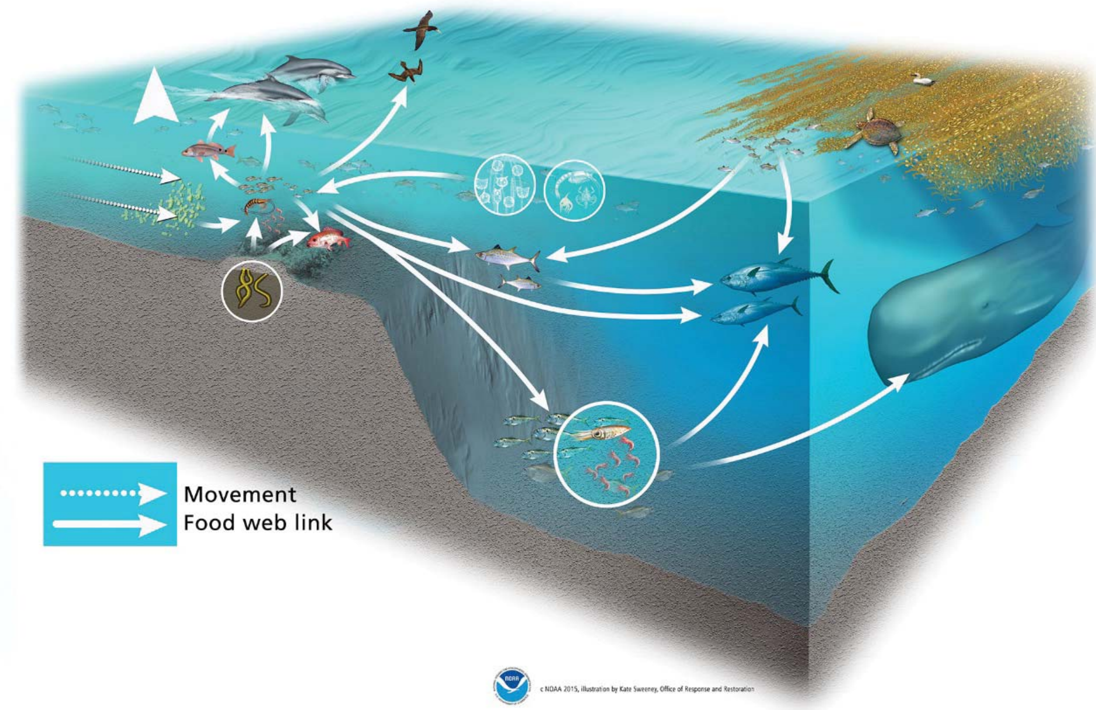
Water Column Resources	Description of Resource
Bacteria	Bacteria are single cell organisms without cell nuclei. Abundant throughout the water column, they serve as important components of the microbial food web (Miller 2004).
Phytoplankton	Phytoplankton are small single cell algae found in the photic zone of the water column, requiring sunlight and nutrients to grow. Phytoplankton abundance typically varies seasonally. Common types of phytoplankton include diatoms and dinoflagellates (Miller 2004). Phytoplankton are the chief "primary" producers in the water column and are an important food source at the base of the marine food web. Phytoplankton contribute to "marine snow," a term used to describe dead and decaying organic detritus falling through the water column (Miller 2004).
Zooplankton	Zooplankton are small, free-swimming animals found within all zones of the water column. Common types of zooplankton include single-celled protozoans, such as foraminifera; gelatinous zooplankton, such as jellyfish; annelids, such as polychaetes; molluscs, such as pteropods; crustaceans, such as copepods; and vertebrates, such as larval fish (Miller 2004). Zooplankton are considered "secondary" producers, feeding on phytoplankton and smaller zooplankton, and they are an important food source for fish and invertebrates. Zooplankton serve as conveyors of energy vertically in the water column, transferring organic carbon and nutrients from the surface waters to the deep water environments. This downward transfer occurs both by active transport (e.g., daily vertical migration) and passive transport (e.g., the sinking of fecal pellets) (Ducklow et al. 2001).
Estuarine-dependent water column species	Estuarine-dependent species include more than 250 species. Representative species ranging from invertebrate secondary producers (e.g., various shrimp and crabs) to low trophic level consumers (e.g., menhaden, anchovies, and striped mullet) to higher trophic level predators (e.g., Atlantic croaker, spotted or speckled seatrout, red drum, striped mullet, sand seatrout, black drum, sheepshead, southern flounder, and some species of shark) (O'Connell et al. 2005). These species are found in estuaries, over the shelf, and in the open ocean, with different life stages typically using different habitats. Estuarine-dependent species may be obligate (i.e., without the estuarine habitat, the species would be unable to survive and/or reproduce) or facultative (i.e., the species may derive a benefit from use of the estuarine habitat, but do not require such use for survival or reproduction). Estuarine-dependent species connect the estuarine and oceanic systems (Able 2005; Able & Fahay 1998; Day Jr. et al. 2013), and are an important food source for the pelagic food web.
Coastal and oceanic epipelagic water column species	Coastal and oceanic epipelagic water column species are those that spend their entire lives on the continental shelf or in the offshore environment, and typically within the epipelagic zone (less than 200 meters below the surface). Species include smaller forage fish (e.g., anchovies, herrings, and sardines) and large predatory fish (e.g., mackerels, tunas, jacks, and sharks). Some large oceanic species, such as tuna, occupy both the surface and mid-water portions of the

Water Column Resources	Description of Resource
	water column (Block et al. 2001; Teo et al. 2007), providing a link between these areas in the food web. All life stages, including eggs and larvae, are important food sources for higher trophic-level organisms.
Mid and deep water column species	Mid-water and deep water column species, found within the mesopelagic zone of the water column (200 to 1,000 meters below the surface), are adapted to little or no light and low food availability. Mesopelagic fishes include lanternfish, bristlemouths, and hatchetfish (Hopkins & Sutton 1998; Quintana-Rizzo et al. 2015). Mesopelagic invertebrates include shrimp, mysids, and squid (Hopkins & Sutton 1998; Passarella & Hopkins 1991; Quintana-Rizzo et al. 2015). The mesopelagic community typically exhibits diel vertical migration, feeding on zooplankton in the uppermost 200 to 300 meters of water at night (Hopkins et al. 1994; Hopkins & Sutton 1998; Lancraft et al. 1988). This migration contributes to the vertical transport of organic matter between the epipelagic zone and the mesopelagic zone. These species are prey items for larger pelagic species such as tunas and billfishes.
Continental shelf reef fish	Shelf reef fish, found on both natural and artificial reefs on the continental shelf, include larger species (e.g., triggerfish, amberjacks, groupers, and snappers) and small cryptic fish (e.g., blennies) (Addis et al. 2013; Dance et al. 2011). Reef fish are recreationally, commercially, and ecologically important and many species are considered overfished stocks (NOAA 2015).
Sargassum	*Sargassum* is a brown alga that floats on the ocean surface. It is a source of primary production and provides habitat and food for sea turtles, marine birds, fish, and invertebrates. It also fills a critical role in nutrient cycling and sedimentation for nearby ecosystems. Designated as Essential Fish Habitat, it provides fish larvae and juveniles protection from predators. It also provides nursery habitat for many important fishery species (e.g., dolphinfish, triggerfishes, tripletail, billfishes, tunas, and amberjacks) and for ecologically important forage fish species (e.g., butterfishes and flyingfishes) (Powers 2012).

4.4.1.3 Ecological Relationships and Processes

Although expansive, the species and habitats of the northern Gulf of Mexico are linked through chemical and physical processes and biological relationships (Chapter 3, Ecosystem Setting). Foodweb dynamics; the movement of organisms between habitats; and the transport of nutrients, sediments, and other materials vertically and horizontally all play a role in the structure and function of the Gulf ecosystem (Chapter 3, Ecosystem Setting).

Predator-prey relationships are dynamic and create an interconnected web of organisms, with energy flowing from primary producers, such as phytoplankton, through a number of trophic linkages to top predators, such as tuna (Figure 4.4-4; (e.g., Althauser 2003; de Mutsert et al. 2012; Masi et al. 2014; Tarnecki et al. 2015). Figure 4.4-4 shows a highly simplified food web, depicting a couple dozen of the thousands of species in the Gulf of Mexico. The figure's simplified depiction does not illustrate how many species occupy different positions in the food web as they grow. For example, a given species of fish may be consumed by certain animals when it is small, but then consume those same animals when it grows to become an adult. The diversity of communities in the water column, the sometimes shifting trophic linkages, and the wide variety of interactions mean that perturbations—such as an injury to one or more components of the food web—may have broader direct, indirect, and sometimes non-intuitive ecological consequences (Fleeger et al. 2003; Fodrie et al. 2014; Peterson et al. 2003; Pimm et al. 1991; Tarnecki et al. 2015).



Source: *Kate Sweeney for NOAA.*

Figure 4.4-4. Simplified foodweb diagram of the shelf and offshore Gulf of Mexico water column.

The active movement of species between habitats is another important ecological characteristic of the Gulf ecosystem (Chapter 3, Ecosystem Setting). As discussed above, some estuarine-dependent water column species move from nearshore to offshore during their life cycle, linking these two areas and their respective food webs. In addition, some species of zooplankton, fish, and other invertebrates migrate vertically in the water column, transporting energy and materials between the surface and deep water zones.

Nutrients, sediment, and organic matter are also transported horizontally and vertically through water movement (Chapter 3, Ecosystem Setting). Currents and winds move water horizontally, connecting the highly productive and nutrient-rich waters of the coastal areas with the more oligotrophic (i.e., lower nutrient) offshore waters; sinking detritus transports organic matter from the surface to deep waters. This detritus includes plant and animal material, marine snow, and fecal pellets.

4.4.2 Approach to the Assessment

Key Points

- A wide diversity of water column species was exposed over a large area and through many pathways. These interactions' complexity necessitated an assessment approach that employed an array of datasets and analyses to characterize DWH oil exposure and subsequent injuries to water column organisms.
- The Trustees applied a combination of field, laboratory, remote sensing, and numerical modeling approaches.
- A fish-health field survey and analysis of fisheries-independent datasets were conducted to determine community level and physiological effects in the water column that were caused by the DWH oil spill.

As discussed elsewhere in this report (Section 4.3, Toxicity), natural resources may be adversely affected via different exposure pathways: either directly (e.g., toxic effects of oil on an exposed species) or indirectly (e.g., through loss of spawning habitat or reductions in prey availability caused by the spill) (Fleeger et al. 2003; Fodrie et al. 2014; Peterson et al. 2003). When natural resources are injured, cascading ecological effects can result (Fleeger et al. 2003; Fodrie et al. 2014; Peterson et al. 2003). These effects include changes in ecological structure (such as altering the abundance or presence of organisms that comprise the community in an area) and ecological functions (such as altering the flow of nutrients and energy). This document's water column injury assessment takes fundamental ecosystem relationships and processes into consideration.

To characterize the oil exposure and subsequent injury to water column organisms, the Trustees used both field and laboratory data. The Trustees collected data on the fate and transport of the oil and on the abundance and distribution of organisms in the water column. Field studies were conducted to document environmental conditions, evaluate exposure, and assess the condition of biological resources. Numerous toxicity tests were conducted in laboratories to determine the toxicity of MC252 oil to various life stages of Gulf water column species (Section 4.3, Toxicity). All of this information—combined with hydrodynamic, biological, and toxicological modeling—was used to estimate the nature and extent of injuries to water column species.

Because of the diversity and complexity of the Gulf ecosystem, the vast area of the northern Gulf of Mexico affected by the oil spill, and the practical challenges of performing scientific studies in logistically challenging habitats (e.g., deep waters with safety concerns), it was not possible to study every species, habitat, and ecological process. Therefore, the Trustees applied an understanding of fundamental ecological relationships and processes to focus on representative species and habitats, using study results to make reasonable scientific inferences about natural resources and services that were not explicitly studied. As described in Ecosystem Settings (Chapter 3), the Trustees relied on this understanding of ecological relationships to develop potential restoration approaches.

This section presents the Trustees' approach to the water column injury assessment. Section 4.4.2.1 presents the conceptual model for the pathway and exposure of water column resources to DWH oil.

Section 4.4.2.2 presents the integrated water column resource assessment approach, including the methods for injury quantification of fish and invertebrate species. Section 4.4.2.3 presents the *Sargassum* assessment approach, and Section 4.4.2.4 documents additional biological assessment approaches not covered in the earlier sections.

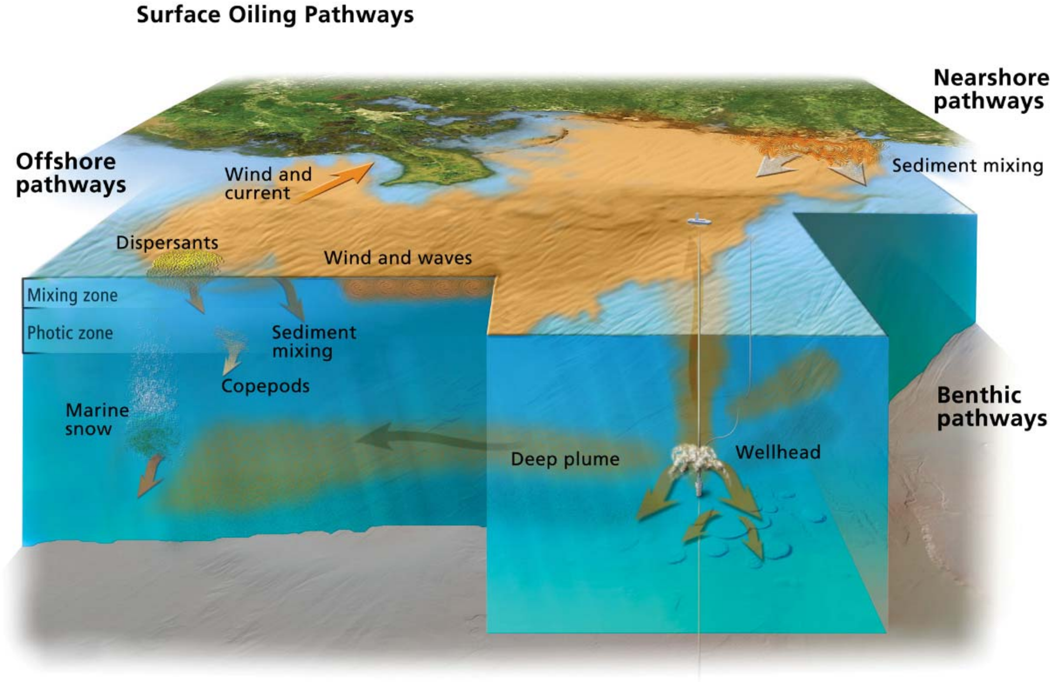
4.4.2.1 Pathways for Exposure

The DWH oil spill impacted a large expanse of the northern Gulf water column, extending from the biologically diverse deep-sea environment to the highly productive coastal waters (Section 4.2, Natural Resources Exposure). As Figure 4.4-5 shows, oil that discharged from the wellhead transported through the water column via five main pathways:

- Oil droplets released from the wellhead rose up through the water column, resulting in the **rising oil plume.**
- Oil was dispersed, both physically and chemically, near the wellhead, and a layer of dissolved oil and oil droplets was trapped at depth and moved with deep-sea currents, resulting in a **deep water oil plume.**
- Oil that reached the surface waters was transported horizontally by winds and currents over great distances, resulting in a large **surface slick** that eventually reached shorelines.
- Oil within the surface slick became mixed in the upper portions of the water column due to natural physical processes and cleanup response actions, resulting in a **subsurface entrained layer.**
- Oil droplets within the water column became attached to particulates, such as detritus or marine snow, and were transported to the benthos and sometimes resuspended, resulting in a **downward flux of particulates**.

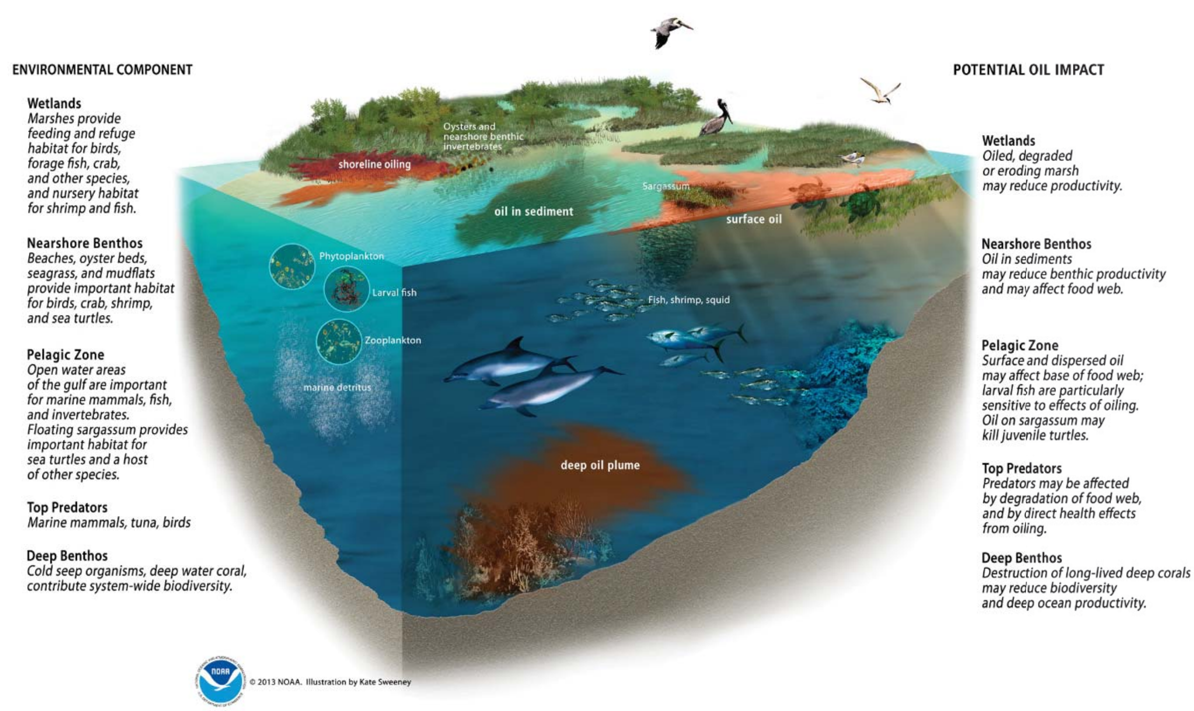
The injury quantification focuses on the first four pathways. The last pathway exposes both water column and benthic resources and is examined in Section 4.5 (Benthic Resources).

Water column resources were exposed to oil in various forms, including oil droplets; dissolved hydrocarbons; oil attached to particulates, such as marine snow; oil-contaminated food; and weathered oil in the surface slick (Section 4.2, Natural Resources Exposure). Figure 4.4-6 illustrates the distribution of key water column resources in relation to their likely oil exposure pathway and potential oil impact. Toxic effects of oil to phytoplankton, zooplankton, and many species of fish and crustaceans have been extensively documented in the literature and NRDA-funded studies (Section 4.3, Toxicity). Ultraviolet (UV) light from the sun is known to increase the toxicity of oil for many species in the upper water column (Section 4.3, Toxicity). Physiological endpoints, such as reduced growth, impaired reproduction, and adverse health effects, have also been observed in the field (Section 4.4.2.2) and supported by laboratory experiments (Section 4.3, Toxicity). Lethal and sublethal impacts at the organismal level could result in larger, population- or community-level effects, such as shifts in abundance, trophic structure, and community structure (Fleeger et al. 2003; Fodrie et al. 2014; Peterson et al. 2003).



Source: *Kate Sweeney for NOAA.*

Figure 4.4-5. Illustration of the DWH oil release pathways.



Source: *Kate Sweeney for NOAA.*

Figure 4.4-6. Water column resources and potential oil impacts.

4.4.2.2 Integrated Water Column Resource Assessment Approach

The Trustees conducted an integrated water column resource analysis to determine and quantify injuries to northern Gulf water column resources. Section 4.4.2.2.1 describes the set of related methods the Trustees used to address the surface slick and subsurface mixed zone; Section 4.4.2.2.2 describes the different set of related methods used to evaluate the rising plume and the deep water plume.

The Trustees' quantification of injury to water column biota is focused on larval fish and planktonic invertebrates because these early life stages are more sensitive to oil exposure (Section 4.3, Toxicity). Injury to adult life stages was evaluated but not quantified. Figure 4.4-7 presents an overview of the Trustees' water column assessment approach, and the following paragraphs describe specific approaches to evaluating empirical data and modeling results. See Section 4.4.2.4 for additional studies the Trustees conducted to evaluate community/population level and physiological effects of the DWH oil spill on water column resources.

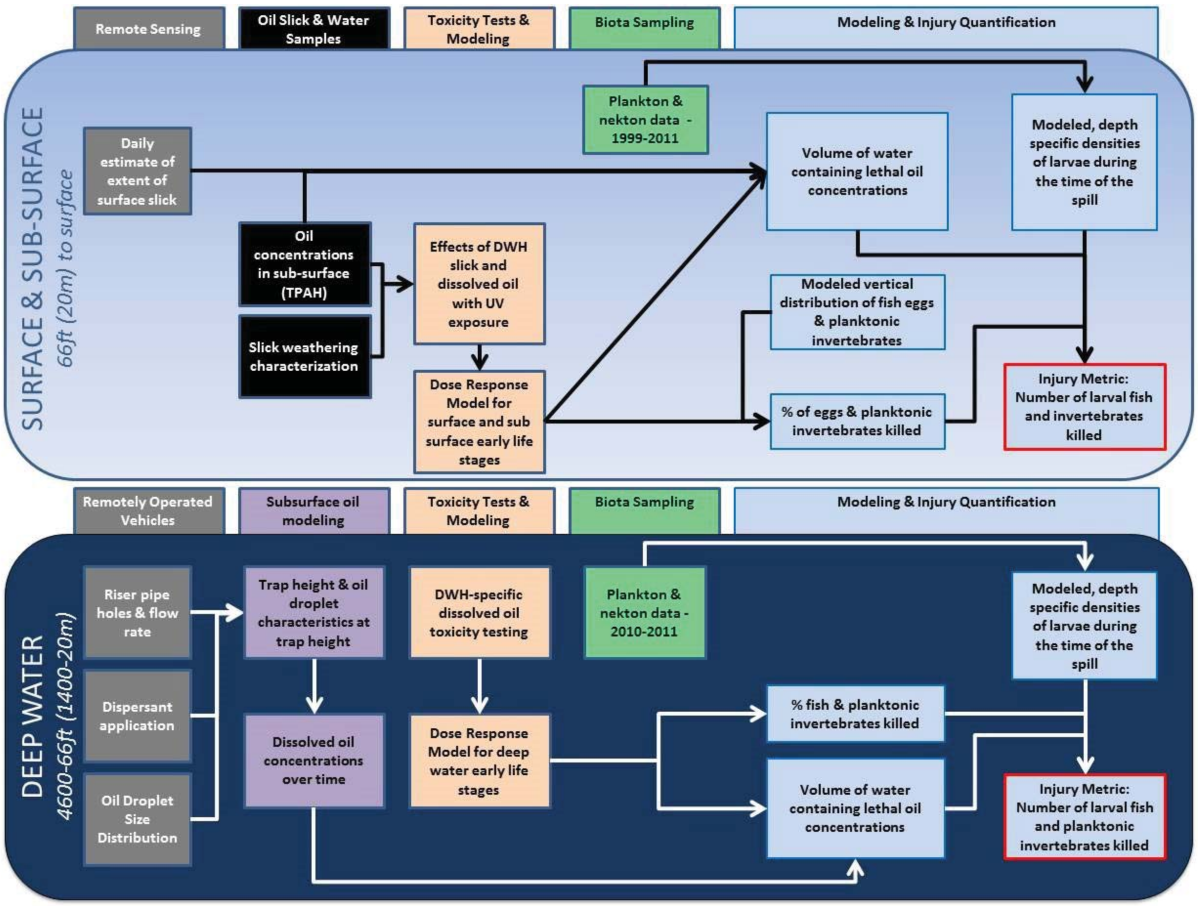


Figure 4.4-7. Approach taken to assess injury to water column habitat and biological resources.

4.4.2.2.1 Surface Slick and Subsurface Mixed Zone

Data from remote sensing, combined with empirical chemistry, were used to quantify, for the duration of the spill, both the area of surface floating oil and the volume of water under the slick that was toxic to water column organisms. To determine the impact of the oil on the biological community in the upper

water column, the Trustees used biological datasets derived from the following sources (French McCay et al. 2015c):

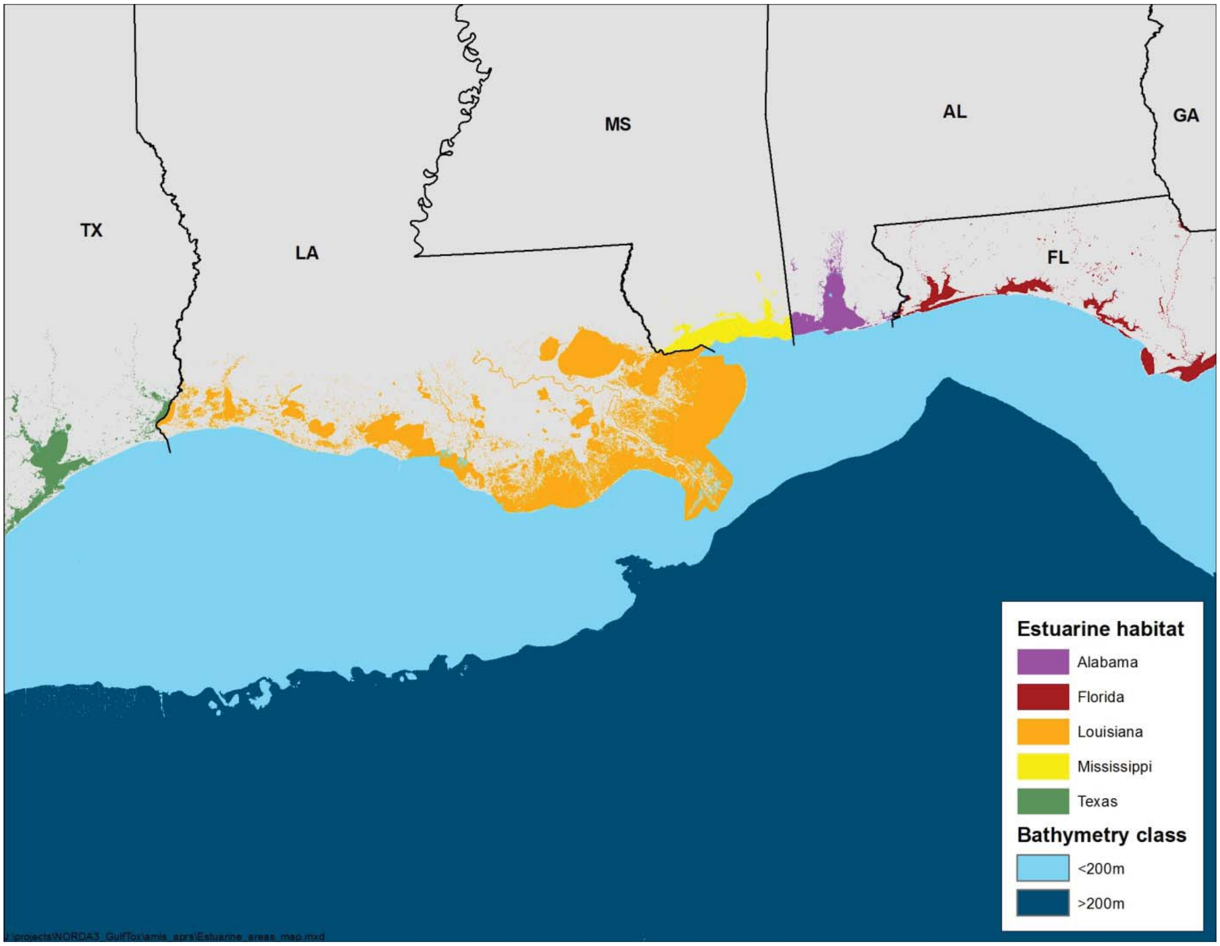
- Historical surveys by the National Marine Fisheries Service (NMFS) Southeast Area Monitoring and Assessment Program (SEAMAP).
- A plankton survey by the Dauphin Island Sea Laboratory's Fisheries Oceanography of Coastal Alabama (FOCAL) program.
- The DWH NRDA plankton program (French McCay et al. 2015c).

The historical data and DWH NRDA data were used to predict the density of eggs and larvae present in surface waters containing floating oil. NRDA toxicity program data (Section 4.3, Toxicity) were then used to generate the percent of eggs and larvae killed by this oil.

The Trustees quantified injury in the surface slick for three distinct zones, which are defined below and shown in Figure 4.4-8:

- An offshore zone, defined as areas where the water is more than 200 meters deep.
- A shelf zone, defined as areas seaward of barrier islands where the water is less than 200 meters deep.
- An estuarine zone, defined as all waters landward of barrier islands.

Distinct offshore, shelf, and estuarine assessments were performed because these areas have different species distributions, toxicity studies, and satellite imagery. However, the approach to quantify injury was generally the same across all three zones.



Source: Travers et al. (2015a); (2015b). Estuarine waters from Cowardin et al. (1979); land modified in Louisiana using Couvillion et al. (2011). Bathymetry adapted from NOAA (2006) and NOAA (2010).

Figure 4.4-8. Map of the north central Gulf of Mexico, distinguishing the offshore zone (depth greater than 200 meters), the shelf zone (areas seaward of barrier islands with water depth less than 200 meters), and estuarine waters (shallow waters inside the nearshore barrier islands).

Surface Oil Observations and Mapping

As discussed in Section 4.2 (Natural Resources Exposure), the Trustees analyzed remote sensing data to delineate the extent of DWH oil slicks. For the water column analyses, the Trustees relied heavily on synthetic aperture radar (SAR) images for estimating the daily spatial extent of surface oil, because SAR has the greatest spatial and temporal coverage of the available remote sensing instruments (Garcia-Pineda et al. 2009; Graettinger et al. 2015). For days when SAR images were unavailable, the areal extent of surface oil was assumed to be the average of the slick area from the previous day and the following day. One limitation in the SAR data is that some days have only a single SAR image that covers just a portion of the Gulf oil slicks (Graettinger et al. 2015). When the SAR data had limited spatial coverage, the Trustees only used available images to estimate the areal extent of the slick—an approach that underestimated areas on these days.

In addition to SAR imagery, the Trustees analyzed imagery from several other airplane- and satellite-mounted sensors, including data from the National Aeronautics and Space Administration's (NASA's) Moderate Resolution Imaging Spectroradiometer (MODIS) and NASA's/the U.S. Geological Survey's (USGS's) Landsat Thematic Mapper. These sensors collect data at wavelengths that include visible spectra (similar to a camera) and infrared (including thermal infrared that detects when an oil slick appears warmer or colder than the surrounding sea). The Trustees integrated the data from multiple sensors into a model that not only estimated the oil slick areal extent, but also estimated coverage of thicker oil (or emulsions) and thinner oil (Garcia-Pineda et al. 2009; Graettinger et al. 2015). Some analyses of injury in the upper water column relied on this integrated model of remote sensing data.

Empirical Chemistry Data

As described in greater detail in Section 4.2 (Natural Resources Exposure), the Trustees collected and analyzed numerous samples of the oil floating throughout the northern Gulf of Mexico to characterize the surface slick chemistry. Floating oil varied in age, from relatively fresh oil that had recently risen from the wellhead to the surface to DWH oil that had remained in the water column for weeks or longer and eventually transported to the surface offshore of marshes and beaches. The chemistry of the floating oil is detailed in Section 4.2 (Natural Resources Exposure).

Multiple sampling studies collected water samples at different depths to assess water column oil concentrations. The subsurface water column injury quantification used a dataset compiled from sampling data documented in multiple sources, including the Trustees' NRDA, the BP NRDA, the Response (cleanup), and the BP Public website (Travers et al. 2015a). The Trustees used this dataset to estimate the distribution of oil in the upper mixed zone of the water column in the offshore, shelf, and estuarine areas. Section 4.4.3.2, below, describes the results of this analysis.

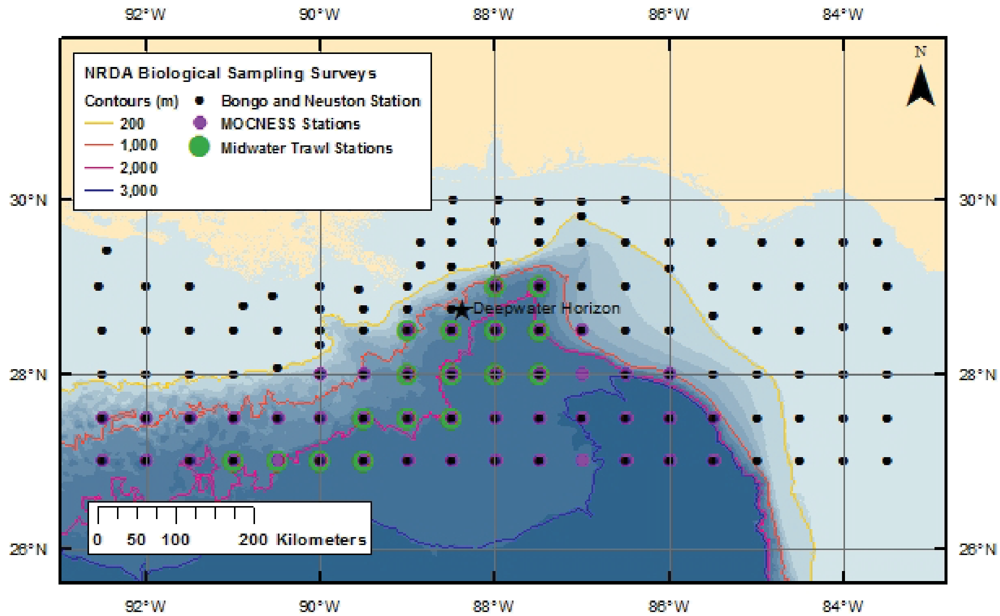
Oil is a complex mixture made up of thousands of organic compounds (NRC 2003). Oil concentrations in the environment are often described in terms of the concentrations of a limited set of compounds found in the oil. Typically, when assessing the effects of oil, researchers focus on the concentrations of PAHs, which are the set of compounds thought to be the most toxic (NRC 2003). The DWH NRDA toxicity testing program generally reported effect concentrations in terms of the sum of 50 PAHs (TPAH50) (Forth et al. 2015; Morris et al. 2015b). Consequently, to assess injuries in the water column resulting from oil and for comparison of toxicity test results, we used TPAH50 to describe oil concentrations.

Empirical Biological Data

To estimate the number of fish and invertebrate species exposed to oil, the Trustees reviewed and analyzed numerous pre-spill data sources. For example, the Trustees reviewed and analyzed 10 years of pre-spill SEAMAP data and technical reports from NOAA and the Bureau of Ocean Energy Management. The data and information from these sources were then used to calculate densities of taxa. In cases where pre-spill data were not available for a given habitat or community, post-spill data were considered. The metadata for the datasets can be found in Table 4.4-2. Maps showing the location of NRDA and SEAMAP sampling are included in Figure 4.4-9, Figure 4.4-10, Figure 4.4-11, and Figure 4.4-12.

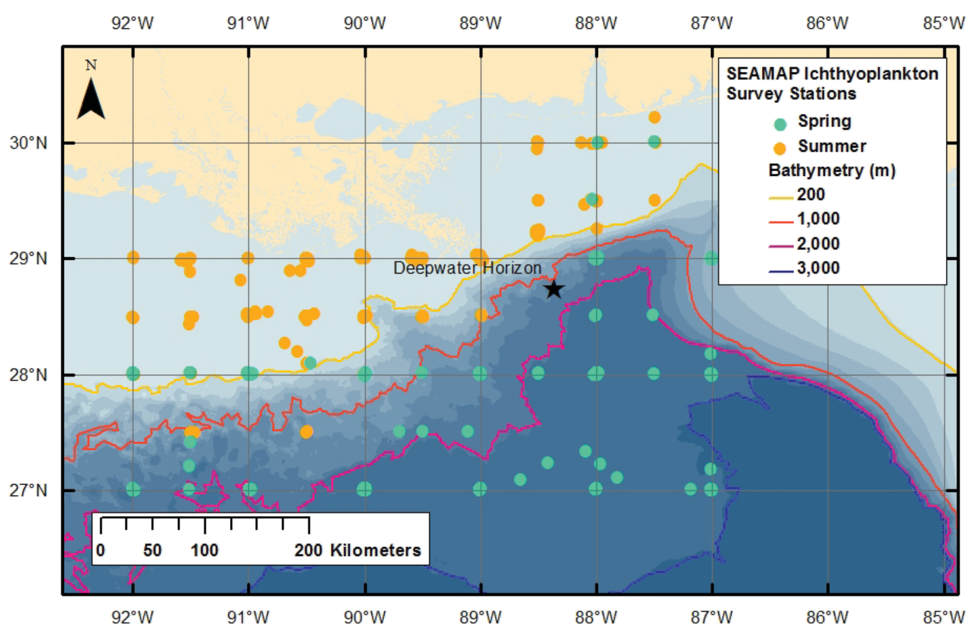
Table 4.4-2. Description of empirical biological datasets used to determine biological densities.

Dataset	Time Period Covered	Description of Dataset
1. SEAMAP Ichthyoplankton Survey	1999–2009	Ichthyoplankton and small juvenile fish densities in the upper 200 meters in shelf and offshore waters
2. SEAMAP Invertebrate Zooplankton Survey	1999–2009	Invertebrate microzooplankton densities (other than decapods) in the upper 200 meters in shelf and offshore waters
3. NRDA Plankton bongo sample data	2011	Decapod larval densities in the upper 200 meters in shelf and offshore waters
4. NRDA Plankton 1 m^2 MOCNESS sample data	2011	Fish and decapod larval densities below 200 meters in offshore waters
5. SEAMAP Shrimp/Groundfish Survey	1999–2009	Juvenile and adult fish and invertebrate densities in the upper 200 meters in shelf waters
6. NRDA 10 m^2 MOCNESS sample data	2011	Micro-nektonic pelagic fish and planktonic invertebrate densities in offshore waters, depths greater than 200 meters
7. NRDA Pisces Midwater Trawl data	2011	Nektonic pelagic fish and invertebrate densities in offshore waters, depths greater than 200 meters
8. Deep Gulf of Mexico Benthos (DGoMB) Survey (Powell et al. 2003; Rowe & Kennicutt II 2009)	2003; 2009	Demersal fish and invertebrate megafauna densities in offshore waters, depths greater than 200 meters
9. NRDA Flying Fish Observations	2011	Juvenile and adult fish in surface waters of shelf and offshore waters
10. Stock Assessment-Based Estimates	1999–2009	Juvenile and adult fish in shelf and offshore waters
11. Estuarine fish and invertebrate densities (Brown et al. 2013)	2013	Estuarine fish and invertebrate densities applicable to waters inside the barrier islands
12. Dauphin Island Sea Lab FOCAL plankton survey	2007–2009	Nearshore (estuarine) larval fish and planktonic invertebrate densities applicable to waters inside the barrier islands



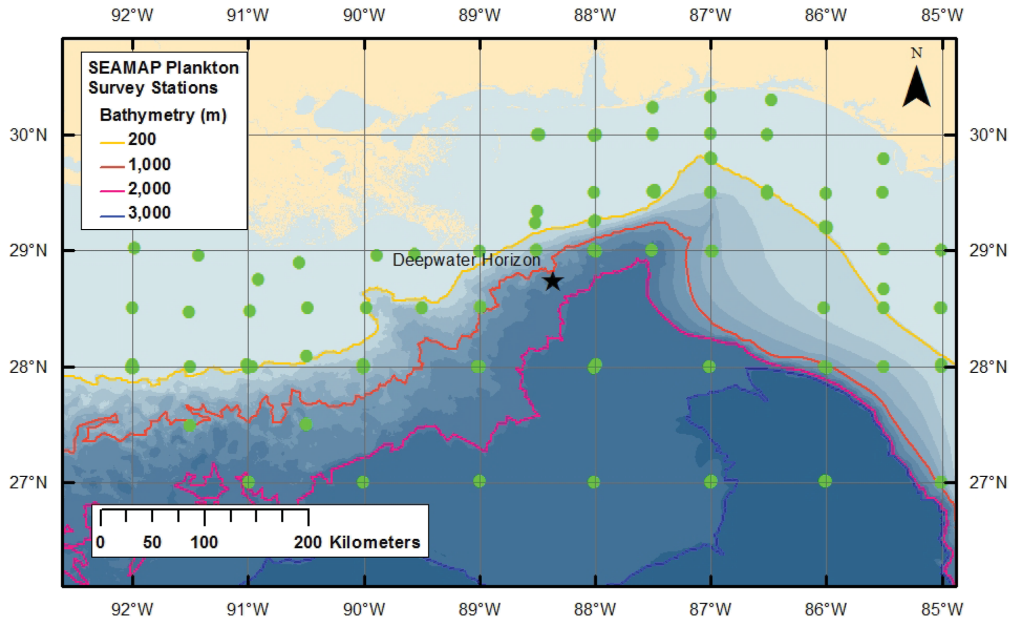
Source: *French McCay et al. (2015c).*

Figure 4.4-9. Location of NRDA biological sampling survey stations. Sampling was primarily conducted using three methods: bongo and/or neuston net tows (black dots), both 1- and 10-square meter MOCNESS sampling nets (purple dots), and midwater trawls (green dots).



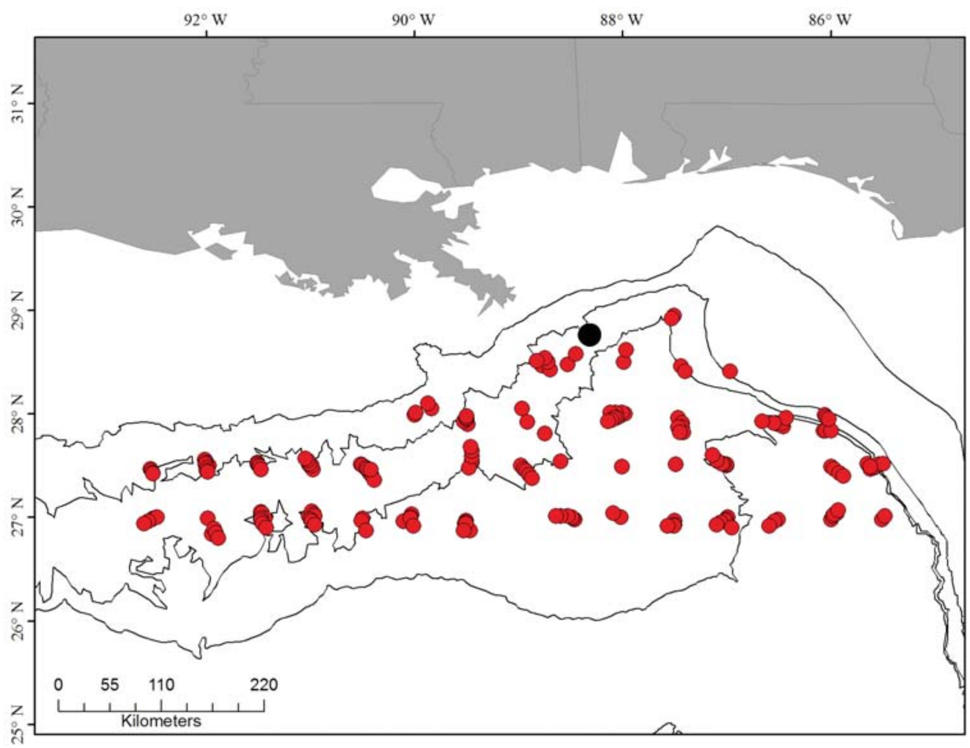
Source: *French McCay et al. (2015c).*

Figure 4.4-10. A portion of the geographic extent and survey station locations of SEAMAP Plankton Survey data used to derive ichthyoplankton densities.



Source: *French McCay et al. (2015c).*

Figure 4.4-11. A portion of the geographic extent and survey station locations used by SEAMAP to calculate invertebrate zooplankton densities.



Source: *French McCay et al. (2015c).*

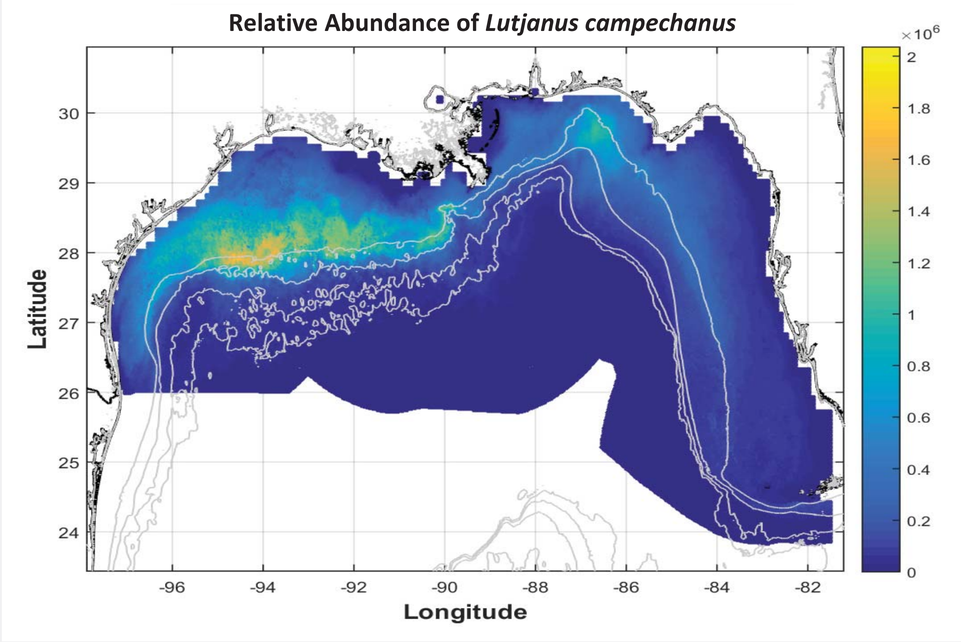
Figure 4.4-12. Locations of samples (red dots) used from the NRDA 10 m^2 MOCNESS surveys, cruise MS7. MC252 Wellhead indicated with the black dot. Black lines represent 200-meter, 1,000-meter, 2,000-meter, and 3,000-meter bathymetric contours.

4.4.2
Approach **to the Assessment**

While these datasets cover a wide range of organisms, data for some groups remain incomplete due to sampling limitations. For example, fast-swimming pelagic species are rarely, if ever, caught in trawls and other sampling gears. Also, most studies only sample smaller fish, typically from age-0 and age-1 year classes. Due to these and other factors, the derived species densities described below and used to calculate injury to water column data should be considered an underestimate of actual species densities.

Generalized Additive Models

Generalized additive models (GAMs) (Hastie & Tipshirani 1990; Wood 2006) are a well-established statistical modeling technique. Using data from historical bongo net sampling across the Gulf of Mexico and a suite of environmental data, GAMs were developed to provide predictions of the relative abundance and distribution of larval fishes in the U.S. Economic Exclusion Zone in the Gulf of Mexico for any day between April 23 and August 11, 2010 (Christman & Keller 2015; Quinlan et al. 2015). Figure 4.4-13 shows the relative abundance of larval red snapper expected in each of more than 400,000 grid cells with a nominal size of about 1.7 square kilometers. The GAMs for red snapper well-represented the seasonal changes in the abundance of red snapper larvae as well as the distributional patterns and how those distributions changed through time. Maps like these, and the data behind them, were used to estimate the abundance and distributional patterns for a variety of larval fishes and invertebrates, and to explore the overlap between surface oil slicks and these organisms.



Source: *John Quinlan, NOAA (2015).*

Figure 4.4-13. Estimated relative abundance of larval red snapper on June 20, 2010, in the U.S. Economic Exclusion Zone. Relative abundance is related to the expected number of larval red snapper per 1,000 square meters based on bongo net sampling. The density values (number per 1,000 square meters) were scaled to the area of the grid cell in this figure. Grey contours depict the 100-, 400-, 1,000-, and 1,500-meter isobaths.

Determining Distribution and Abundance of Taxa and Life Stages

Using SEAMAP ichthyoplankton data from 1999 to 2009, statistical techniques were applied to predict larval densities for the period of the spill. For a subset of species present in the Gulf that were abundant, represented different life history characteristics, or were of particular economic or ecological concern, generalized additive models (GAMs) were developed using the SEAMAP Ichthyoplankton Survey bongo net catch data and spatially and temporally correlated environmental characteristics (e.g., location, depth, temperature). The daily density maps derived from the GAMs were used as baseline densities present during the spill from April to July 2010 (Christman & Keller 2015). For other species or taxonomic groups, the average abundance of that taxon was used. Average abundances represent the daily densities and were generated either seasonally offshore (i.e., spring and summer) or monthly in the nearshore estuarine zone. Though average density estimates were established for each taxon individually, confidence ranges around these averages were large due to the patchy distributions of many planktonic organisms. Thus, where estimates are provided that sum across species, the confidence interval was generated using the pooled data for those taxa.

Many pelagic spawning fish have positively buoyant eggs—some of which were found in the upper mixed layer and interacted with both the surface slick (Gearon et al. 2015) and contaminated water under the slick. The Trustees used models to estimate the vertical distribution of eggs and developing embryos in the water column (Wobus et al. 2015) and to assess eggs' and embryos' exposure to the oil. The exposure calculations were made using the distribution of TPAH50 concentrations and toxicity testing results, as described below.

The vertical distribution of eggs in the upper water column depends on the wind speed at the surface, the diameter of the eggs, and the eggs' density (in grams per cubic centimeter) compared to the water density. When eggs are larger and less dense, their relative concentrations near the surface increase. On the other hand, relative egg concentrations near the surface are reduced with smaller, denser eggs and higher wind speeds, which increase dispersion and push eggs deeper into the water column. To quantify the vertical distribution of eggs as a function of wind speed, egg diameter, and egg density in grams per cubic centimeter, the Trustees used VertEgg—a model that estimates the static distribution of eggs in the water column, but does not simulate the movement of eggs over time (Ådlandsvik 2000; Wobus et al. 2015).

Modeling of Toxicological Effect

To calculate a range of potential toxicity to ichthyoplankton and zooplankton exposed to DWH oil, three species of fish and two species of invertebrates, all indigenous to the Gulf of Mexico, were selected. The sensitivity of these species to DWH oil represented the range of sensitivity (with and without UV light) observed across a wide range of taxa that were tested for the DWH NRDA. For purposes of this analysis, waters not subject to UV-PAH phototoxicity were those at least 20 meters below the surface or turbid enough to preclude significant UV light penetration based on field data (Lay et al. 2015a) for early life stage fish. See Section 4.3 for a more detailed explanation of the Trustees' toxicity program, including explanations of toxicity endpoints and associated acronyms used in this section.

Toxicity in the Absence of Sunlight

The selected species that represent the low and high end of the range of sensitivity in the *absence* of UV light were the more sensitive bay anchovy (*Anchoa mitchilli*) and the less sensitive red drum (*Sciaenops ocellatus*) (Morris et al. 2015c). The concentration that kills 20 percent of the test organisms (Section 4.3, Toxicity)—known as the LC_{20}—for bay anchovy (based on a 48-hour test) and red drum (based on a 72-hour test) are 1.3 and 21.9 µg/L TPAH50, respectively. For invertebrates, the low and high sensitivity species and their corresponding LC_{20} values are copepod (*Arcartia tonsa*; LC_{20} = 33.5 µg/L TPAH50 based on a 96-hour test) and blue crab (*Callinectes sapidus*; LC_{20} = 79.0 µg/L TPAH50 based on a 48-hour test), respectively. These ranges were used to evaluate TPAH50 water column concentrations in waters that do not receive appreciable UV light.

Toxicity in the Presence of Sunlight

Biota near the ocean surface are exposed to sunlight and DWH oil. The Trustees investigated photo-induced toxicity on Gulf early life stage fish and invertebrates and determined that, consistent with the literature, UV light can greatly enhance the toxicity of DWH oil on early life stage organisms (Section 4.3, Toxicity). In fact, the average amount of UV light measured in the Gulf of Mexico during the spill can increase the toxicity of DWH oil by approximately 10 to 100 times over 1 day (Lay et al. 2015b; Morris et al. 2015b). Therefore, a UV adjustment factor was derived to apply to dose-response curves for several fish and invertebrate species. Adjustments to dose-response relationships were made using the average daily integrated UV intensity for the Gulf of Mexico during the spill (1,550 mW-s/cm^2, UV-A, 380 nm; Lay et al. (2015a).

For both fish and invertebrates, two species were selected to represent the low and high end of the range of sensitivity, similar to the approach for habitats without UV light, described above. For the UV-adjusted toxicity, the low and high sensitivity fish and invertebrate species and the magnitude of the increased toxicity based on each adjustment relative to their sensitivity in the absence of UV light are: bay anchovy (14-fold increase), mahi-mahi (*Coryphaena hippurus*; 15-fold increase), copepod (27-fold increase), and blue crab (27-fold increase). UV-adjusted dose-response curves were used to estimate the percent mortality for these species.

In addition to exposure to oil entrained in the water, organisms may also have been exposed to floating oil slicks or sheens through direct contact. As described in Section 4.3, the Trustees determined the toxicity of very thin surface sheens of oil in the presence of varying levels of UV light (Morris et al. 2015a). For purposes of this analysis, a very thin sheen is approximately 1 micron (µm) thick, approximately 40 times thinner than a single human hair. When exposed to the integrated average dose of UV light in the Gulf of Mexico over the course of the spill, the toxicity (percent mortality) of thin surface sheens to red snapper (embryo), bay anchovy (embryo), spotted seatrout (embryo), and mysid shrimp (juvenile) is 85, 89, 100, and 100 percent mortality, respectively. Based on these results, percent mortalities were developed for organisms exposed to the surface slick zone:

- 91 percent mortality—the average across the three fish species—was used for the two UV-exposed representative fish species (bay anchovy and mahi-mahi).

- 100 percent mortality—the result for mysid shrimp—was used for the two representative invertebrate species (copepod and blue crab).

Estimated Mortality from Oil Exposure

To estimate the mortality to fish embryos and invertebrates caused by oil exposure, the Trustees assessed oil concentrations and UV doses encountered during the spill. Applying a Monte Carlo approach (i.e., repeated random sampling) (Robert & Casella 1999) using the egg and TPAH50 concentration distributions described above, the Trustees generated probabilistic estimates of TPAH50 concentrations at different depths that any given egg beneath a surface slick might have encountered over the course of the spill.

For each randomly selected egg, a UV dose was calculated by applying a UV extinction coefficient to the average incident UV at the water surface. Extinction coefficients were based on an average of offshore measurements in the Gulf of Mexico (Lay et al. 2015a). The Trustees used the combination of TPAH50 and UV to calculate the percent mortality using the UV-adjusted dose-response curves for the "sensitive" and "less sensitive" species, described above (Morris et al. 2015b; Morris et al. 2015c). The Trustees used the calculated mortality for each of the thousands of simulated scenarios to estimate the percentages of total mortality over the water column. The Trustees used a similar approach for invertebrates, except that invertebrates were assumed to be evenly distributed vertically in the water column (Travers et al. 2015b).

For the estuarine waters, the Trustees evaluated exposure only to floating oil. The estuarine waters generally contain high concentrations of sediment, and UV light does not penetrate deep in these turbid waters. In this analysis, oil slick toxicity was estimated only to the depth where 10 percent of incident UV light remains, which is approximately 0.2 meters beneath the surface, based on measurements made in Barataria Bay (Lay et al. 2015a). The average mortality was therefore estimated from the water surface to a depth of 0.2 meters beneath the surface (Section 4.3, Toxicity).

Estimated Production Foregone

The production foregone model estimates the lost future growth (i.e., production) that the killed organisms would have produced had they otherwise lived their normal lifespan. It does not include losses that would have occurred from reproduction or additional generations. The biomass of organisms directly killed as the result of the DWH spill represents the weight of the organisms at their death; the production foregone model determines the biomass (additional weight) these organisms would have accrued as they grew from their early life stages into adults or until they died naturally or were harvested. Production foregone uses information on mean growth and survival for each species. Assessing production foregone allows for a more thorough representation of spill-related injuries to water column organisms than would be captured by calculating what is lost by the direct kill alone. Results of the production foregone model are measured in biomass, which can be used to address biological concerns and can be informative when considering restoration needs.

Production foregone was calculated for larvae of 29 fish species that have growth models reported in state, federal, or international stock assessments, including snappers, tunas, mackerels, seatrout,

croakers, and billfish. As part of their stock assessment development, the needed growth and mortality rates have been well studied and reviewed by fisheries managers, such that the production models based on these inputs are robust. Invertebrate production foregone was calculated using the growth models of two species: blue crab (*Callinectes sapidus*) and white shrimp (*Litopenaeus setiferus*). Each of these invertebrate species has an available federal stock assessment or has been extensively studied. The white shrimp growth model was applied to shrimp where adults grow to similar size (i.e., approximately 100 to 200 millimeters in length and maturing in approximately 1 year). For crabs, the blue crab growth model was applied to all crabs in that family (i.e., to the family Portunidae). Development of the production foregone model and estimations of production foregone per individual killed are described in French McCay et al. (2015a).

4.4.2.2.2 Rising Oil and Deep Plume

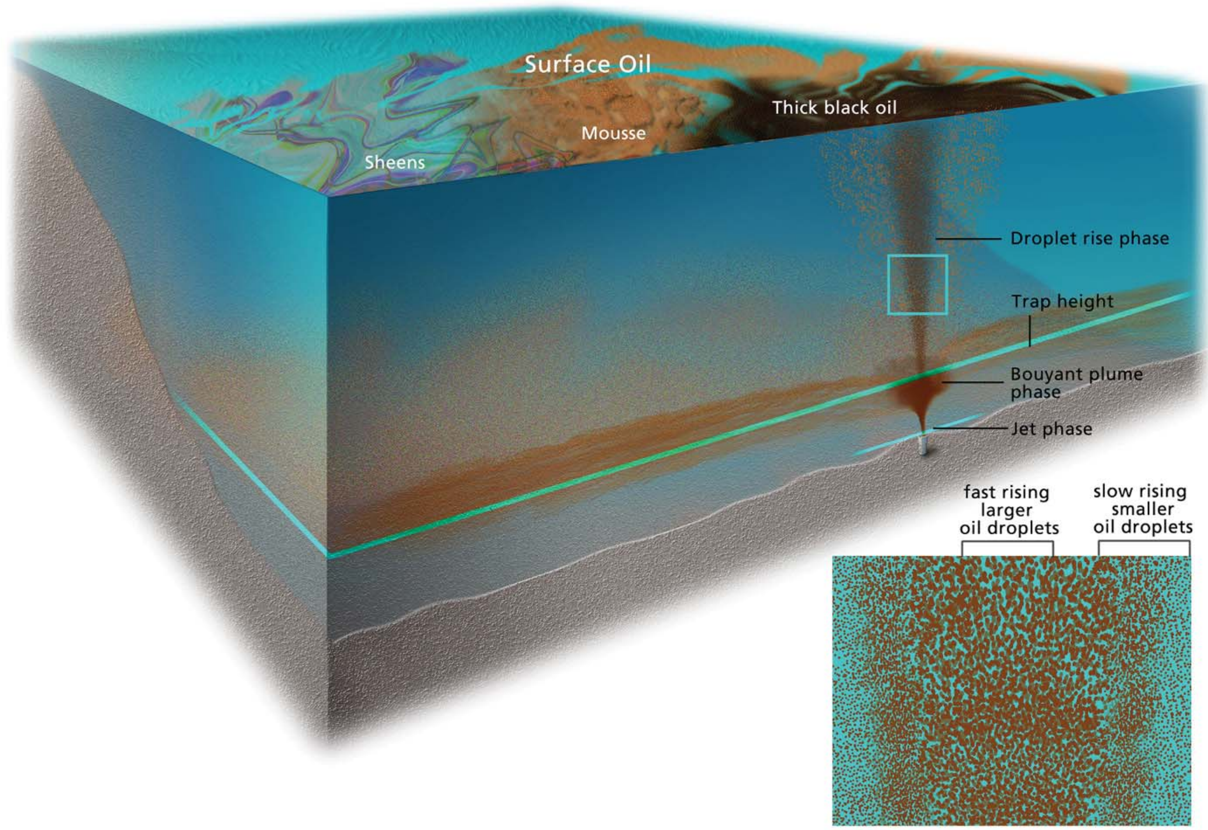
Empirical chemistry data and a highly developed modeling approach were used to quantify the volume of water contaminated with PAHs for the duration of the spill. To determine the impact of the contaminated oil on the biological community in the rising cone of oil and the deep water plume, the Trustees used various biological datasets to predict the density of ichthyoplankton and invertebrate larvae present in the water column. Data derived from the NRDA toxicity program (Section 4.3) were used to generate the percent of larvae killed through contact with the rising oil.

Modeling of Oil at Depth

The Trustees modeled the fate and transport of the rising "cone" of oil from the blowout through the deep water column.

Figure 4.4-14 is a conceptual model of the blowout and rising oil droplet phases whereby oil droplets of various sizes moved upward through the water column. The OILMAPDeep blowout model (Spaulding et al. 2015) evaluates the jet and buoyant plume of the release from the broken riser. The model determines the neutral-buoyancy depth, also known as the "trap height," which is where oil droplets separate and are subsequently transported horizontally by currents and vertically by their individual buoyancies. Models were used to estimate the oil masses and droplet sizes of the released oil droplets. This analysis was based on the U.S. v. BP et al. (2015) findings of 4.0 million barrels of oil released from the reservoir and 3.19 million barrels of oil discharged to the Gulf of Mexico. The amount discharged each day between April 20 and July 15, 2010, was assumed proportional to the daily release volumes estimated by the Flow Rate Technical Group (McNutt et al. 2011).

Oil droplet mass, size, and location estimates from the Spaulding et al. (2015) analysis were used as input to the Spill Impact Model Application Package (SIMAP) oil fate model (French McCay 2003, 2004). SIMAP then evaluated weathering (i.e., dissolution and degradation), movements, and concentrations of oil and components (e.g., PAHs) from the trap height to the ocean surface (French McCay et al. 2015b). SIMAP also predicted TPAH50 concentrations over time in a three-dimensional spatial grid extending from water column depths of 1,400 meters beneath the surface up to 20 meters beneath the surface. The uppermost 20 meters were evaluated as part of the surface layer analysis.



Source: *Kate Sweeney for NOAA.*

Figure 4.4-14. Conceptual model of the blowout and rising oil droplet phases and a depiction of surface oil features.

SIMAP results were synthesized into daily TPAH50 concentration distributions that were used to evaluate toxicity. Specifically, the estimated TPAH50 concentrations were used with the dose-response curves developed for more and less sensitive fish and invertebrates in the absence of UV (see “Modeling of Toxicological Effect” section, above) to estimate the percent mortality in each concentration grid cell, assuming a daily exposure. The effect of UV on toxicity was not considered for the SIMAP-modeled TPAH50 concentrations, because UV does not appreciably penetrate to the depths considered in the SIMAP model (i.e., 20 to 1,400 meters beneath the surface). The estimates of percent mortality multiplied by volume affected were summed daily, and by depth layers at 20-meter intervals, to estimate volumes of water where plankton were killed. These numbers were multiplied by the numbers of organisms per volume (see “Empirical Biological Data” section, below) to calculate the numbers killed.

Empirical Chemistry Data

As oil continued to be released from the wellhead, scientists on both Response and NRDA cruises collected information regarding water and components of the water column to determine where the deep oil was going. However, it was difficult to sample the rising cone due to restrictions on vessels near the wellhead. Nonetheless, 47 water samples that were collected from May to August 2010, within

5 kilometers of the well and from a depth of 40 to 1,000 meters beneath the surface (below the upper mixed zone and to the top of the deep plume) were identified by forensic analysis as MC252 oil. The maximum TPAH50 concentration in these forensically matched samples was 19 µg/L (Payne & Driskell 2015a).

Later in the spill, concern over the deep oil plume grew and the deep plume was sampled more thoroughly. The concentrations of oil-derived chemicals were highest nearer the well and generally decreased with distance from the well. Particulate oil was present in the plume 155 kilometers from the well, and dissolved hydrocarbons from the oil could be detected up to 267 kilometers from the well. Forensic analysis indicated that more than 800 samples collected at depths of at least 1,000 meters contained MC252 oil. The highest TPAH50 concentration among these samples was 68 µg/L. Other indicators of the deep plume (e.g., presence of dispersant-derived chemicals, fluorescence, and decreased dissolved oxygen) were measured as far as 412 kilometers southwest of the well (Payne & Driskell 2015a).

Empirical Biological Data

Long-term biological data like those for surface waters (e.g., SEAMAP) do not exist for the deep water pelagic zone. Many deep water species occupy specific depth ranges in the mesopelagic and bathypelagic zones. The deep mid-water trawl nets and depth-stratified MOCNESS nets used during the NRDA were the most comprehensive sampling conducted to date for pelagic animals of the deep Gulf of Mexico waters. These data were used to describe the distribution and abundance of deep water fish and invertebrates exposed to oil (Sutton et al. 2015). Acoustic data collected for the NRDA were used to examine both the depths and locations of the deep layers of fish and invertebrates and their daily vertical migrations in the water column (Boswell et al. 2015).

Modeling of Toxicological Effect

The toxicological approach for deeper water is the same as previously described for surface waters (in Section 4.4.2.2.1), with two exceptions. First, UV effects are not considered for deeper water because UV does not penetrate to the depths considered (Lay et al. 2015a). Second, different species were selected (see Section 4.4.2.2.1) to bracket a range of sensitivity in the absence of UV.

4.4.2.3 *Sargassum* Assessment

The Trustees assessed exposure and injury to *Sargassum* and associated fauna. The Trustees documented direct oiling of *Sargassum* and then determined the following: the areal extent of surface oiling from the DWH spill, the density (i.e., percent cover) and area of *Sargassum* in the northern Gulf of Mexico, the area of *Sargassum* exposed to oil, and the amount of *Sargassum* area foregone due to lost growth caused by exposure to oil. The major inputs for the *Sargassum* assessment are described below and summarized in Table 4.4-3.

Table 4.4-3. Description of *Sargassum* assessment inputs.

Dataset or Model	Time Period Covered	Description of Dataset
Extent of Surface Oiling		
1. NOAA oil-on-water product	2010	Daily polygons of oiling from April to July 2010
***Sargassum* density calculations**		
2. NSF aerial surveys	2010, 2011	Photographs of *Sargassum* from low altitude aerial surveys of the northern Gulf of Mexico
3. USGS/NASA Landsat data	2010, 2011	Landsat data from 2010 and 2011

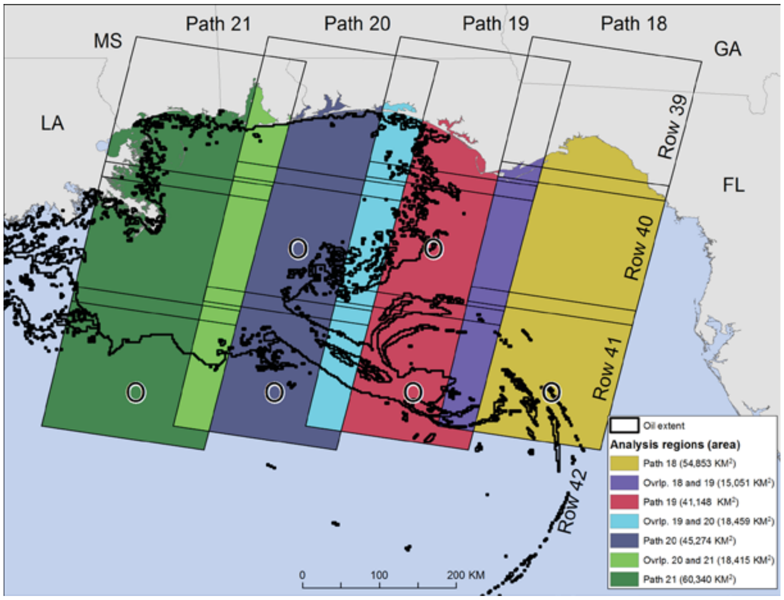
Extent of Surface Oiling

To estimate the area and extent of surface oil to which *Sargassum* was exposed, the Trustees relied on an intensive analysis of daily surface oil coverage based on multiple satellite sensors from April to August 2010 (Graettinger et al. 2015). To assess the upper and lower bounds of exposure, the Trustees developed two sets of cumulative oiling footprints based on two levels of percent cover of surface oil and two time periods. The surface oiling dataset provides information on the area of the ocean where there was oil with a given percent being covered by "thick oil." These polygons include ocean area that had surface oiling for at least 1 day. Based on expert opinion informed by field observation of both surface oil and *Sargassum*, the Trustees selected two cutoffs of the percent area covered by thick oil to bound the likely exposure of *Sargassum* to oil: areas with greater than 5 percent thick oil and areas with greater than 10 percent thick oil.

Sargassum moves across the northern Gulf of Mexico with currents and winds, taking approximately 6 weeks (S. Powers, personal communication, September 16, 2015) to move across the full range of the area affected by the spill. As a result, all the *Sargassum* in the area affected by oil is replaced after 6 weeks. Accordingly, exposure of *Sargassum* to surface oil was assessed in two separate 6-week timeframes: the early part of the spill (April 25 to June 5, 2010) and the latter part of the spill (June 6 to July 17, 2010). *Sargassum* present at the beginning of the spill was assumed to be oiled and injured as it moved through the spill area for 6 weeks and then replaced by additional *Sargassum* over the following 6 weeks. The total amount of *Sargassum* injured by the spill is the sum of quantities in areas of thick oil for these two time periods (Doiron et al. 2014).

Density of *Sargassum* and *Sargassum* Growth

The Trustees estimated *Sargassum* density (i.e., percent cover) by combining Landsat satellite images and low-altitude aerial photography. Landsat provides broad spatial coverage of the northern Gulf of Mexico (see Figure 4.4-15), but lacks sufficiently fine resolution to identify all *Sargassum* on the ocean surface. While low altitude aerial photographs have limited spatial coverage, they provide superior resolution in identifying *Sargassum*. Through a statistical analysis of satellite and low-altitude images matched by date and location, the Trustees developed a mathematical formula to estimate *Sargassum* percent cover (Hu 2015; McDonald 2015).



Source: *Hu (2015).*

Figure 4.4-15. Landsat paths used in the analysis of *Sargassum* percent cover estimates. "O" denotes areas that were only recorded in 2010. Landsat is a satellite run by USGS and NASA to collect land-surface data. In 2010, USGS increased Landsat coverage over the Gulf of Mexico to capture more images of the DWH oil spill.

An additional measure of *Sargassum* injury is the surface area foregone due to lost growth caused by oil exposure. As *Sargassum* moves across the northern Gulf of Mexico, it grows at a rate of 4 percent per day (LaPointe 1986; as cited in Powers 2012). The Trustees used this growth rate, combined with information on *Sargassum* in oil-contaminated surface waters, to calculate a range of surface area foregone.

4.4.2.4 Additional Biological Assessment

The Trustees conducted several additional studies to evaluate community/population level and physiological effects of the DWH oil spill on water column resources other than those described above. To investigate fish health, the Trustees worked with researchers to implement a field-based fisheries survey. The Trustees also used long-term fisheries-independent datasets to investigate population level impacts to commercially and recreationally important species. These investigations were used to evaluate injury to adult life stages. However, for reasons described below, these injuries were not quantified.

Fish Health Study

In the wake of the DWH oil spill, an increasing number of anecdotal reports were received of red snapper with skin lesions found in northern Gulf of Mexico waters. In response, the Trustees collaborated with academic researchers to quantify the prevalence and persistence of fish with lesions and to collect information about the health of fish beyond their external wounds. This research was

conducted in a series of cruises along the continental shelf and within the Louisiana coastal estuary and marsh habitats. The scientists recorded observations of external abnormalities, measured and weighed whole fish and selected organs, and conducted necropsies. Additionally, fish and tissues samples were sent to analytical laboratories to determine many health endpoints, such as tissue damage (histopathology), age (otolith analysis), blood condition (blood chemistry and blood cell counts), and presence of pathogens.

Fisheries-Independent Data Analysis

To compare fish and invertebrate populations before and after the DWH oil spill, researchers at NOAA's Northwest Fisheries Science Center (NWFSC) analyzed fisheries-independent survey data (Ward et al. 2015). In this analysis, SEAMAP trawl survey data were used to assess population changes and detect shifts in catches across 51 species of fish and invertebrates. SEAMAP data series were expressed as standardized catch-per-unit effort (CPUE) and assessed using multivariate state-space models (Ward et al. 2015) and by intervention analysis (Scheuerell et al. 2015; Ward et al. 2015). The state-space models focused on detecting changes in standardized residuals of abundance, while the intervention analysis focused directly on CPUE. Both modeling approaches incorporated relevant environmental conditions (e.g., temperature, salinity, and dissolved oxygen) as covariates, as these factors may affect fisheries' abundance over time. In addition, data from trawl, seine, and gillnet surveys conducted by the Louisiana Department of Wildlife and Fisheries (LDWF) were used to assess changes in the population density of 12 fish and invertebrate species following the DWH oil spill. Catch records were expressed as standardized monthly CPUE and modeled with a delta-generalized linear modeling approach (Ward et al. 2015). The analyses incorporated environmental conditions (e.g., temperature, salinity, and turbidity) as independent variables in the models.

The Trustees used SEAMAP data and conducted population modeling to evaluate the potential effects of the oil spill on abundance and recruitment of red snapper (Tetzlaff & Gwinn 2015). The SEAMAP data used in these analyses included the early fall plankton survey, the fall groundfish survey (predominantly age-0 fish), and the summer groundfish survey (predominantly age-1 fish). Using these data, the catch of age-0 and age-1 red snapper were modeled for the eastern and western Gulf of Mexico through 2012 (Tetzlaff & Gwinn 2015). In addition, a before-after-control-impact analysis was performed to evaluate red snapper abundance before, during, and after the DWH oil spill in the impacted area (i.e., within the area of the Gulf of Mexico that was impacted by the DWH oil spill) and in a control area (i.e., outside the area of the Gulf of Mexico that was impacted by DWH oil). Depth, dissolved oxygen, and salinity were included as covariates in the model (Tetzlaff & Gwinn 2015). This analysis extends work described in the SEDAR *Gulf of Mexico Red Snapper Stock Assessment Report* (A.G Pollack et al. 2012; A.G. Pollack et al. 2012; SEDAR 2013).

Lastly, the Trustees investigated changes in recruitment and growth rates of red snapper on reefs in the northern Gulf of Mexico following the DWH oil spill (Patterson III 2015). Fisheries-independent data were collected using two methods: hook-and-line gear (i.e., bottom and vertical long lines) on or near artificial reefs in coastal Alabama and near petroleum platforms in coastal Texas, and remotely operated vehicles (ROVs) deployed on natural and artificial reefs sites in Alabama and northwest Florida. Age estimates in these datasets were derived from otolith analysis or age-length relationships. Various

analyses and statistical tests were conducted using these fisheries-independent data to examine changes in red snapper recruitment and growth rates following the DWH oil spill.

4.4.3 Exposure

Key Points

- Following the blowout, DWH oil spread throughout the Gulf of Mexico water column, resulting in the deep-sea oil plume, rising oil plume, surface slick, and subsurface oil entrainment.
- Water column resources were exposed to DWH oil, and PAH accumulation was documented in the marine food web.
- *Sargassum* and surface oil are both transported by the same physical processes. Thus, as one would predict, *Sargassum* and oil were observed accumulating together in convergence zones (i.e., where surface waters come together).
- Understanding species distributions and life history patterns over time and space allowed the Trustees to determine that exposure occurred to different species and life stages both spatially and temporally.

The DWH blowout resulted in an unprecedented volume of oil transported throughout the water column, exposing an array of diverse and productive habitats and species. The Trustees used NRDA empirical data, modeling, and studies from the scientific community to document the spread of DWH oil through the water column and exposure to water column resources. The pathway of oil and exposure to water column resources is described for the surface slick and subsurface mixed zone (Section 4.4.3.1) and the rising oil and deep plume (Section 4.4.3.2). Evidence of oil exposure to *Sargassum* and the associated community is also described (Section 4.4.3.3).

4.4.3.1 Surface Slick and Subsurface Mixed Zone

Surface waters are the most biologically productive areas of the ocean as plankton (including the larvae of many economically important marine species) growth is enhanced due to the presence of nutrients in sunlight. The result is a congregation of life that forms the foundation for the marine food web.

Following the DWH blowout, a portion of the oil rose through the water column to the surface. Once at the surface, the oil slick spread across thousands of square kilometers and was transported by winds and currents over great distances, eventually reaching the northern Gulf of Mexico shorelines. Various physical factors influenced the persistence of oil at the surface (see Section 4.2). Some oil volatilized into the air and some was removed mechanically or by in situ burning. Wind and wave action and application of dispersants resulted in some oil within the surface slick becoming mixed in the upper water column. Entrainment of smaller oil droplets can result in dissolved hydrocarbon compounds in the water column.

Oil in the Subsurface Mixed Zone of Offshore and Shelf Waters

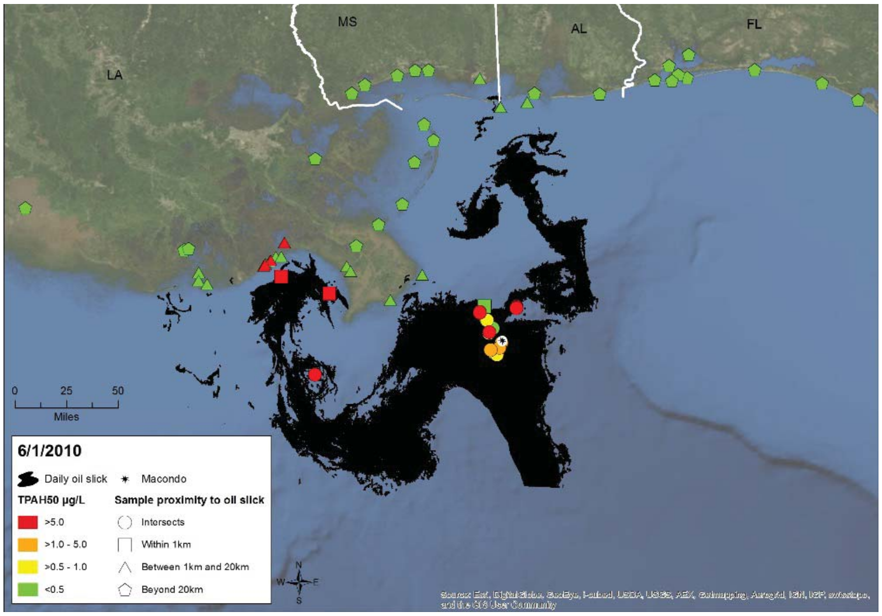
Floating oil was observed on the surface throughout the 87 days that oil flowed from the wellhead, and persisted for more than 3 weeks after the wellhead was capped (Section 4.2, Natural Resources

Exposure). The Trustees used satellite images to determine the areal extent and cumulative number of days where oil was observed on the sea surface (Section 4.4.2.2.1; Section 4.2, Natural Resources Exposure). This analysis has shown that 112,100 square kilometers (43,300 square miles) of open ocean surface water were exposed to oil—an area roughly the size of the state of Virginia (Graettinger et al. 2015). At its peak, oil covered more than 39,600 square kilometers (15,300 square miles) of the sea surface on a single day—an area about 10 times the size of Rhode Island (Graettinger et al. 2015).

Field-collected water samples were used to define the concentrations of oil resulting from entrainment. Oil concentrations were described as the sum of 50 PAHs (TPAH50) for comparison to toxicity test results (Section 4.2, Natural Resource Exposure; Section 4.3, Toxicity). Since most oil in the upper mixed zone was from surface slicks, the Trustees used the surface oil footprint to focus their analysis of subsurface waters. Samples used to evaluate subsurface mixed zone contamination were those collected both in the top 50 meters of the water column and at locations under or proximate to surface oil (defined by the daily SAR imagery) on the day collected. Samples were designated as "intersects SAR" if they were collected under the footprint of floating oil.

Samples located outside the floating oil footprint were grouped into three additional proximity groups: less than 1 kilometer from the floating oil, 1–20 kilometers from the floating oil, and more than 20 kilometers from the floating oil. Samples that were collected on dates that did not have a SAR image available were not assigned to an oil slick proximity group. Water samples collected within surface oil slicks were most likely to contain oil, and these samples generally had higher TPAH50 concentrations than samples collected at some distance from floating oil. The frequency of measured TPAH50 concentrations greater than 0.5 µg/L illustrates this point. Although we used dose-response curves rather than a single threshold to estimate mortality of biota, this TPAH50 concentration (0.5 µg/L) was selected because it is sufficiently high to harm sensitive life stages of biota in the presence of UV light (Section 4.3, Toxicity) (Morris et al. 2015b). Among samples in the uppermost 2 meters of the water column, 54 percent of samples that intersected the oil slick footprint had TPAH50 concentrations above this concentration; however, only 15 percent of samples within 1 kilometer of floating oil, 5 percent of samples within 20 kilometers of floating oil, and 2 percent of samples beyond 20 kilometers of floating oil exceeded a concentration of 0.5 µg/L. Ultimately, given the strong relationship between proximity to floating oil and elevated PAHs in the underlying water column, the Trustees focused subsequent evaluations on only those samples that were collected within the footprint of the floating oil.

Figure 4.4-16 further illustrates how TPAH50 concentrations in surface waters varied with distance from floating oil on 1 day of the spill: June 1, 2010.



Source: *Travers et al. (2015a).*

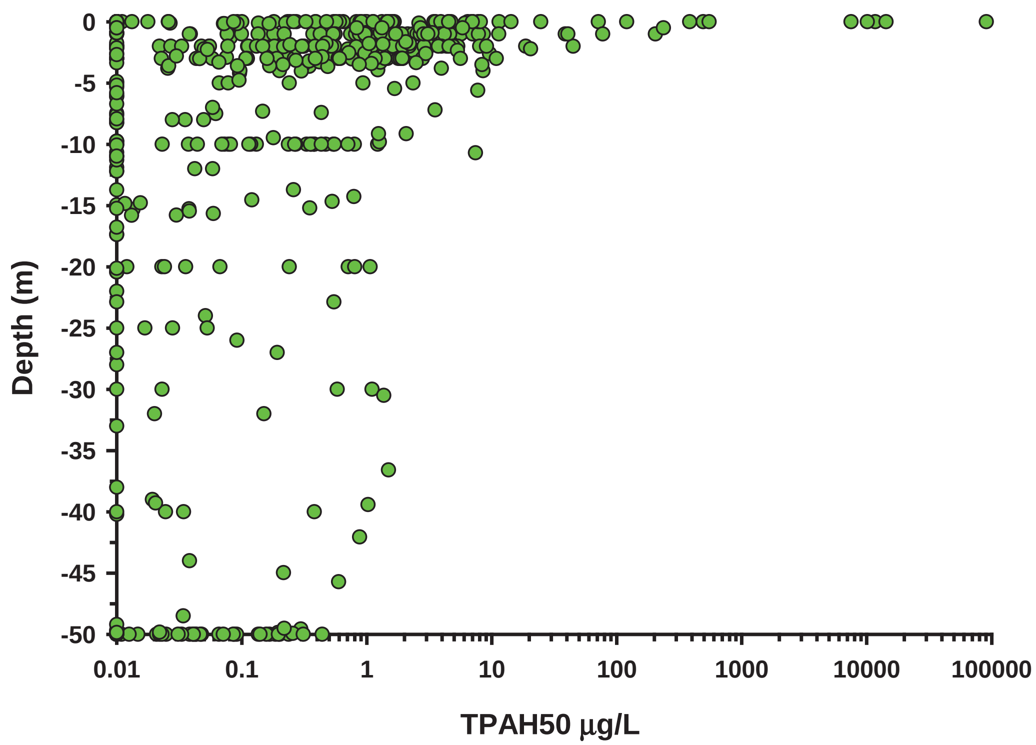
Figure 4.4-16. Example comparing the extent of surface oil (shaded black area) as determined from SAR imagery and water samples collected in the upper mixed zone on 1 day of the spill: June 1, 2010. The various colors indicate ranges of TPAH50 concentrations in water column samples collected from 0–20 meters depth, with red indicating the highest concentrations and green indicating the lowest concentrations. The symbol shape indicates the distance between the sampling location and floating oil on the sampling date.

The Trustees examined TPAH50 concentration as a function of depth beneath the surface using samples collected within or beneath the oil slick footprint, as determined from SAR analyses. These data were used to derive distributions of TPAH50 concentrations for different depth intervals (Figure 4.4-17). Those distributions, in turn, allowed for determining the range of PAHs to which an organism at that depth would have been exposed.

Below depths of 20 meters, PAHs were not detectable or were only detectable at low concentrations; the exception was for samples near BP's Macondo well, which may have been collected in the rapidly surfacing oil. An upper mixed layer depth of 20 meters is also consistent with conductivity, temperature, and depth (CTD) data collected during many of the cruises over the course of the DWH oil spill. Grennan et al. (2015) found that the average depth of the upper, mixed layer in the vicinity of the DWH spill site was approximately 16 meters, but extended to depths of 29 meters at some times. Based on the available data, we focused our analysis of surface oil effects on the upper 20 meters of the water column.

Some samples were collected at the surface, or a depth of 0 meters. Although oil concentrations in these samples would represent what an organism at the surface of the ocean might encounter, they would not necessarily represent concentrations in water beneath the surface slick. To evaluate water beneath the slick, these surface samples were excluded.

Approximately 380 water samples were collected at depths of 0.1 to 20 meters beneath the surface and under oil slicks. Most of these samples contained detectable TPAH50 concentrations, but 19 percent contained no detectable PAHs. The Trustees used the measured water concentrations to develop a statistical distribution describing the range and vertical distribution of TPAH50 concentrations under floating oil (Travers et al. 2015a).This is a limited dataset, particularly given the great spatial extent of the oil covering the Gulf of Mexico. Therefore, estimates of TPAH50 concentrations used in the analyses have inherent uncertainties.



Source: Data obtained from DIVER; figure from Travers et al. (2015a).

Figure 4.4-17. The figure shows TPAH50 levels in water column samples collected at the surface or beneath surface slicks over the course of the spill (green dots). Depth refers to the depth below the water surface at which the sample was collected from 0 to 50 meters. The 19 percent of samples with TPAH50 concentrations less than 0.01 µg/L are plotted at 0.01 µg/L. The Trustees used data to assess injuries in the upper water column from 0 to 20 meters below the surface.

The Trustees also forensically evaluated selected water samples collected in the upper 20 meters (65 feet) of the water column. For this analysis, care was taken to exclude samples that may have included the surface slick oil as a part of the sample. The Trustees confirmed that DWH oil was present in near-surface mixed zone water samples as far as 96 kilometers in most directions from the wellhead (Payne & Driskell 2015a). Through extensive sampling, the Trustees verified that samples of ambient water in the Gulf of Mexico (i.e., waters not affected by the DWH spill) have almost undetectable concentrations of PAHs. Specifically, NRDA water samples collected in the upper 20 meters (65 feet) of the water column in areas unaffected by the DWH spill had an average concentration of less than 0.06 µg/L (Payne & Driskell 2015a).

Oil in the Estuarine Waters

In estuarine waters, the Trustees evaluated water chemistry data in areas where oil was floating. These areas included Terrebonne, Barataria, and Mobile Bays, and Chandeleur and Mississippi Sounds. Consistent with methods used for the offshore areas, the Trustees considered the sample locations relative to oil slicks detectable in SAR imagery collected on the same day. Of the more than 3,700 nearshore/estuarine water samples collected between April and August, 2010, most were collected prior to the arrival of floating oil or in places away from floating oil. Only 120 of these samples were collected within 1 kilometer of an oil slick detectable in a SAR image on the same day. A 1-kilometer buffer was used in the estuarine waters because of the highly patchy nature of floating oil in these areas.

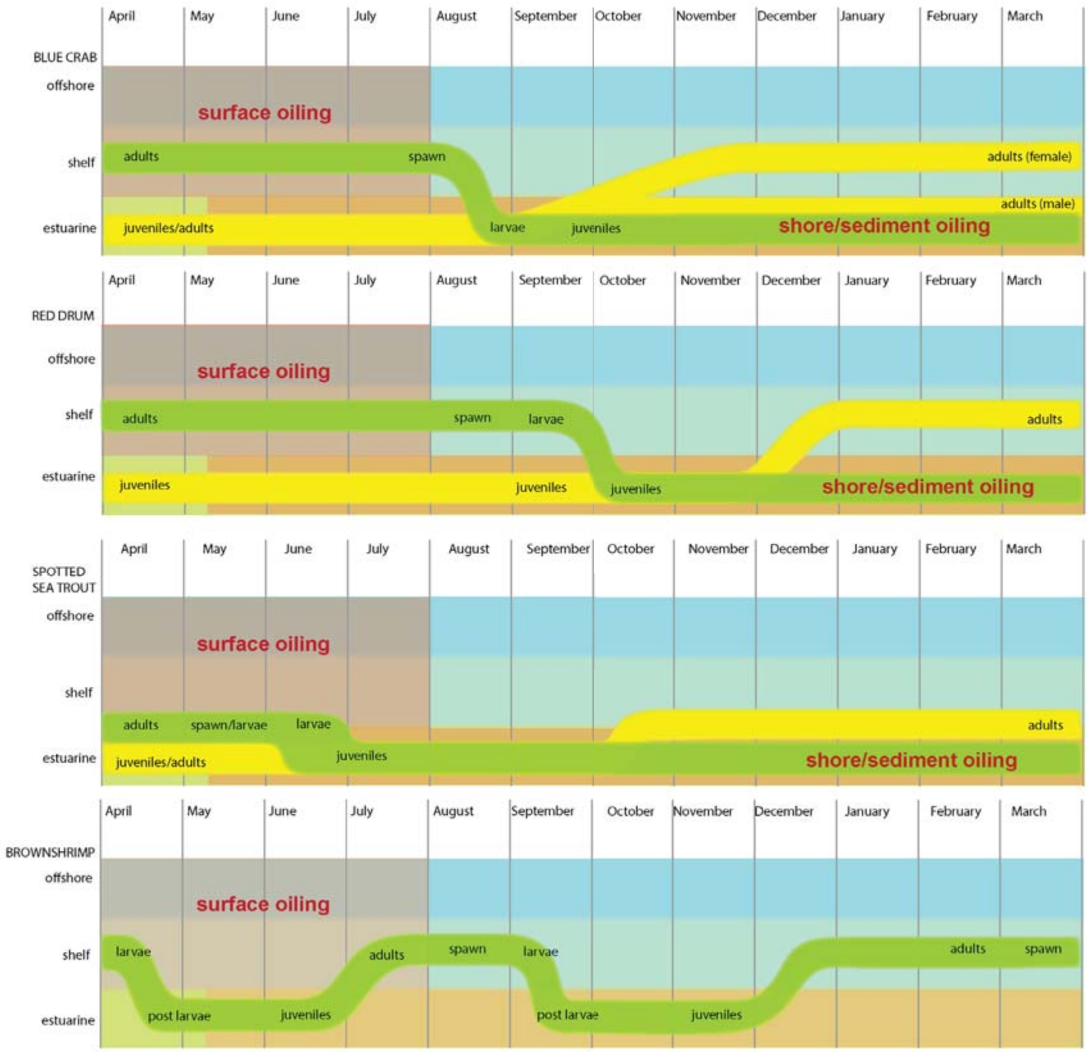
Oil concentrations in the estuarine or nearshore water samples collected near SAR-detected oil slicks were further evaluated based on whether they were collected at the water surface or at depth. Most of the samples were either collected at the water surface or the sample depth was not reported. Within this group of surface samples, TPAH50 concentrations varied from trace levels to 29 µg/L. Of the 24 samples that researchers collected below the water surface and that were associated with surface slicks, 10 had non-detectable PAHs; the TPAH50 concentrations found among the remaining 14 subsurface samples were 0.05 to 0.7 µg/L (Travers et al. 2015a).

Ultimately, the number of water analyses that researchers collected in estuarine waters near surface oil slicks during the spill was quite limited, resulting in considerable uncertainty about estuarine water concentrations associated with floating oil. However, the available data suggest that concentrations of TPAH50 were relatively low in estuarine waters below surface oil slicks. Therefore, estimates of natural resource injuries in estuarine waters relied on other lines of evidence such as the adverse effects of oil slicks (rather than PAHs) on biota (Morris et al. 2015a). The Trustees also conducted a forensic assessment of nearshore water samples collected during the year subsequent to the spill. DWH oil was forensically identified in 361 samples demonstrating that DWH oil was present in the nearshore or estuarine water column during the DWH spill or in the months that followed. Furthermore, DWH oil persisted in subsurface waters in some areas into 2011 (Payne & Driskell 2015b), long after floating oil was visible on the waters. The Trustees' analysis indicated that these samples contain dissolved components possibly leaching from previously deposited oil sources in the nearshore environment (Payne & Driskell 2015b).

Biological Distributions in Relation to Oil in the Upper Water Column

Many organisms are found in the subsurface mixed zone and regularly come in contact with the surface of the ocean. The persistence of floating oil on the surface of the Gulf of Mexico for nearly 4 months was a route of exposure for water column organisms, either through direct exposure to the oil sheen or to water contaminated by oil, dissolved hydrocarbons, and dispersants under the surface slick (Section 4.2, Natural Resources Exposure).

As Figure 4.4-18 illustrates, many fish and invertebrates species spawn in the estuarine, shelf, and offshore waters of the Gulf of Mexico during the spring and summer, releasing eggs and larvae into the upper water column. Thus, the potential for impact to early life stages is great.



***Source:** Kate Sweeney for NOAA.*

Figure 4.4-18. Timing and location of fish and invertebrate life stages in relation to surface and shoreline oiling. Many estuarine-dependent species at different life stages are present in estuarine and shelf waters of the Gulf of Mexico during the spring and summer, overlapping with the timing of the DWH oil spill. Adults typically move to shelf waters or tidal passes to spawn. Following spawning, eggs and larvae are released into the water column, resulting in the potential exposure of these early life stages to the surface slick and subsurface oil entrainment. The larvae are eventually transported back into estuaries via winds and currents, exposing these same organisms to shoreline and sediment oiling as post-larvae, juveniles, or adults. The green and yellow bars in the top three figures represent different cohorts.

For example, using fisheries datasets and modeling, researchers estimated that the DWH oil spill overlapped 15 to 19 percent of high quality early life stage habitat for blackfin tuna during June and July 2010, 11 to 14 percent for mahi-mahi (dolphinfish), and 5 to 7 percent for sailfish (Rooker et al. 2013). Similarly, Muhling et al. (2012) reported that, on a weekly basis, up to 5 percent of bluefin tuna spawning habitat was likely impacted by the surface oil. Two tagged adult bluefin tuna were in close proximity to BP's Macondo well on the day of the accident and remained nearby for several weeks. Both

fish putatively spawned in late April or early May in waters affected by the incident (Wilson et al. [In Press]).

Eggs of many pelagic fish species, such as mahi-mahi, are positively buoyant and are suspended in the water near the surface of the ocean until they hatch (Gearon et al. 2015), which could lead to high exposure to oil in the presence of the surface slick. Larval life stages of fish and crustaceans are transported by tides and currents, which could result in exposure to contaminated water. The SEAMAP ichthyoplankton dataset indicates that fish eggs were the taxonomic group found in the greatest density both on and off the shelf in both the spring and summer (French McCay et al. 2015c).

Several field studies reported by the scientific community suggest DWH oil exposure and PAH accumulation occurred via the marine food web:

- Researchers reported that mesozooplankton collected from the northern Gulf of Mexico showed evidence of exposure to PAHs and a PAH distribution similar to DWH oil (Mitra et al. 2012). The authors concluded that the DWH oil spill may have contributed to contamination in the northern Gulf ecosystem (Mitra et al. 2012).
- In a study conducted along the Mississippi Gulf Coast, Xia et al. (2012) measured significantly higher PAH concentrations in Mississippi seafood (i.e., fishes, shrimps, crabs, and oysters) in the months directly following the DWH oil spill, compared to samples measured at the later part of the study. Although PAHs were detected, all tested samples were below public health levels of concern (Xia et al. 2012).
- In an offshore fish survey, researchers documented relatively high concentrations of PAH metabolites in the bile of red snapper collected in 2011 in the northern Gulf of Mexico (Murawski et al. 2014). Consistent with the decreasing DWH oil exposure footprint over time, significant declines in PAH metabolites in red snapper bile were observed from 2011 to 2012 (Murawski et al. 2014; Snyder et al. 2015).
- Researchers also reported that PAH concentrations in the liver of reef fishes increased up to 20-fold between summer 2010 and fall 2010 and 2011 (Romero et al. 2014).

In response to human health concerns, a large effort was also conducted to test Gulf seafood for contaminants (Fitzgerald & Gohlke 2014; Ylitalo et al. 2012). For example, the federal and Gulf state agencies analyzed more than 8,000 seafood samples, including fish, shrimp, crabs, and oysters, collected in federal waters of the Gulf of Mexico (Ylitalo et al. 2012). Seafood samples consisted of edible muscle tissue (fillets) of whole fish or groups of small shellfish. Overall, PAHs and dispersants were found in low concentrations or below the limits of detection (Ylitalo et al. 2012). When detected, the concentrations were at least two orders of magnitude lower than the U.S. Food and Drug Administration (FDA) level of concern for human health risk (Ylitalo et al. 2012). Similar results were found from a study by Fitzgerald and Gohlke (2014), which tested the edible muscle tissue (fillets) of seven species of reef fish, including red snapper, red grouper, and tilefish, for PAHs, metals, and dispersants. Of the 92 samples analyzed, dispersants were not detected, and only two had detectable levels of PAHs and all were below the FDA level of concern (Fitzgerald & Gohlke 2014). Although these results may appear contrary to the ones

discussed above, differences in the types of tissue sampled likely explain the discrepancies between studies. Fish are known to efficiently metabolize and eliminate PAHs (Stein 2010; Varanasi et al. 1989), typically resulting in relatively low or undetectable concentrations of PAHs in their muscle tissue just days after exposure (Stein 2010; Varanasi et al. 1989); conversely, PAH concentrations are typically highest in the bile and liver of fish after exposure (Varanasi et al. 1989).

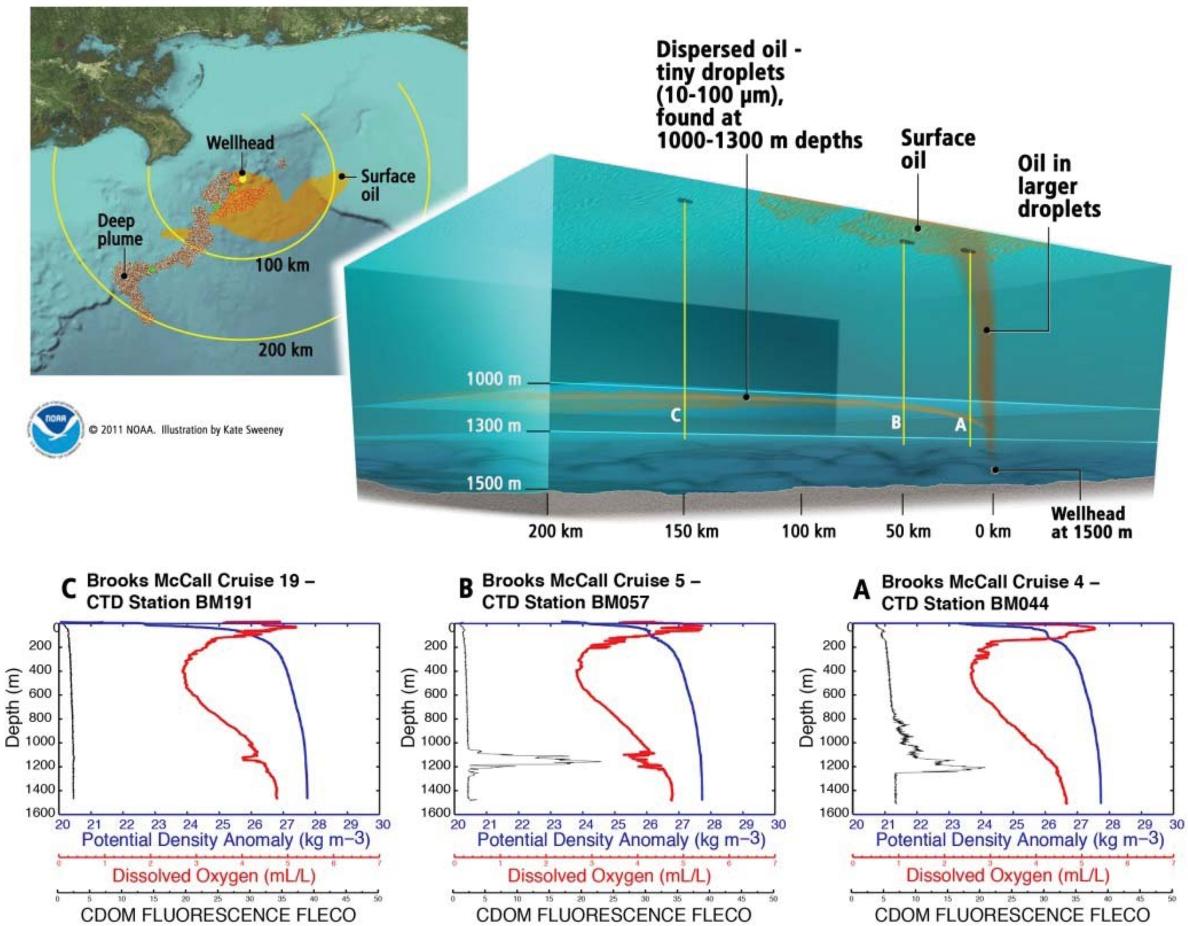
In addition to evaluating PAH concentrations in organisms, other analytical approaches were used to evaluate exposure. For example, based on stable isotope ($\delta^{13}C$) and radioisotope (^{14}C) analysis of plankton and fish, researchers concluded that petroleum-based carbon may have entered the planktonic (Chanton et al. 2012; Cherrier et al. 2013; Graham et al. 2010) and shelf reef fish food webs (Tarnecki & Patterson 2015). Additionally, researchers at the University of South Florida analyzed trace elements in otoliths of offshore fish species, including red snapper, red grouper, and southern hake, all collected following the DWH oil spill (Granneman et al. 2014a, 2014b). The researchers observed trace element anomalies in otolith profiles that occurred during the timeframe of the DWH oil spill event (Granneman et al. 2014a, 2014b). However, the authors note that some of the elements that changed during this time period were closely associated with salinity (Granneman et al. 2014a).

4.4.3.2 Rising Oil and Deep Plume

Oil released from the broken wellhead both dispersed at depth and rose through nearly a mile of water (Section 4.2, Natural Resources Exposure). Large oil droplets (greater than 1 millimeter in diameter) rose quickly—within a few hours to a day—to the ocean surface. Medium-sized oil droplets (between 100 microns and 1 millimeter in diameter) rose to the surface over the course of several days, during which time they were transported by currents away from the wellhead. High turbulence and the injection of dispersants at the source caused oil to be dispersed at the wellhead, which created small oil droplets and particles that remained near the release depth. These smaller oil droplets and dissolved hydrocarbons moved with the deep-sea currents, resulting in a deep-sea oil plume. The composition of the released gas-liquid mixture changed over time and space as the result of dilution, changes in pressure, dissolution, and addition of other constituents such as dispersants, methanol, and anti-foaming additives. Microbial consumption of gas and lighter fractions of oil were also documented (Valentine et al. 2010).

Research conducted for the NRDA during the response effort and research conducted by the academic community successfully located, tracked, and measured hydrocarbon concentrations in the rising oil and deep plume (see Figure 4.4-19). Although sampling was often excluded in the area nearest the wellhead due to safety concerns, water samples collected from the rising cone of oil were forensically matched to Macondo oil; these samples had a maximum TPAH50 concentration of 19 µg/L (Payne & Driskell 2015a). Sampling results indicated the presence of a plume approximately 1,000 meters beneath the surface and extending 10–35 kilometers from the wellhead (Camilli et al. 2010; Diercks et al. 2010; Hazen et al. 2010; Reddy et al. 2012), and the plume contained elevated petroleum hydrocarbon concentrations (Camilli et al. 2010; Diercks et al. 2010; Reddy et al. 2012) with TPAH concentrations reaching 189 µg/L (Diercks et al. 2010). Researchers also observed reduced dissolved oxygen concentrations in the deep plume (Du & Kessler 2012; Hazen et al. 2010; Kessler et al. 2011).

As described in Section 4.4.2.2.2 above, the Trustees conducted simulations of the rising cone of oil and deep plume (French McCay et al. 2015b). Over the course of the release, the model-estimated maximum TPAH50 concentrations in the cone and deep plume just above the source were 218 µg/L and 872 µg/L, respectively. The Trustees also estimated the volume of water with TPAH50 concentrations greater than 0.5 µg/L in these two areas. The maximum volume in the cone was estimated at 33 billion cubic meters (8.7 trillion gallons) and within the deep plume was 3.5 billion cubic meters (930 billion gallons). The modeling approach and results are described in more detail in (French McCay et al. 2015b).



Source: *Kate Sweeney for NOAA.*

Figure 4.4-19. Oil transport through the Gulf of Mexico water column, illustrating the deep-sea plume and rising oil. The lower figures A–C show CTD vertical water profiles measured on the Brooks McCall cruises. The depth below the ocean surface is shown on the left side of the profiles; the profiles extend from the bottom of the ocean (at 1,500 meters depth) to the surface. The CTD profiles provide information about the density of the water (blue), the dissolved oxygen content (red), and fluorescence that can indicate the presence of oil (gray). A decrease in dissolved oxygen and an increase in fluorescence at depth indicates the presence of the deep plume.

The oil released at the wellhead yielded a complex pathway of oil contamination that affected the Gulf of Mexico's bathypelagic and mesopelagic waters. NRDA surveys at these depths documented an enormous diversity of mesopelagic and bathypelagic fish, with more than 450 species identified. Some

of these fish, including lanternfish, bristlemouths, and hatchetfish, were in high abundance (Sutton et al. 2015). These species could have been exposed to spill-related chemicals in various ways: directly to oil droplets or dissolved hydrocarbon compounds; through ingestion of oil droplets, contaminated water (e.g., oil droplets, dissolved hydrocarbons), or contaminated particles (e.g., detritus, marine snow); or through feeding on contaminated food, such as smaller fish, smaller invertebrates, phytoplankton, and zooplankton.

Field studies reported by the scientific community suggest oil exposure and PAH accumulation in the mesopelagic food web. For example, researchers reported post-spill muscle PAH concentrations observed in 2010 and 2011 in mesopelagic fishes were up to 10-fold higher than pre-spill levels observed in 2007 (Romero et al. 2014). In addition, researchers measured depletions in ^{13}C stable isotopes in two mesopelagic fishes and one shrimp species collected following the spill; these researchers concluded their results suggest carbon from the DWH oil spill was incorporated into the mesopelagic food web (Quintana-Rizzo et al. 2015).

4.4.3.3 Exposure of *Sargassum*

Sargassum is typically present in offshore waters throughout the northern Gulf of Mexico, including the area from Louisiana to the Florida Panhandle. In 2010, it was present in the area of surface oiling resulting from the spill. Both surface oil and *Sargassum* are subject to the same physical processes, leading to their accumulation in convergence zones. Thus, *Sargassum* located within the surface oiling footprint was likely co-located with areas of surface oiling, especially areas where thicker amounts of oil accumulate. This *Sargassum* along with any associated fauna was subject to injury.

During the months following the spill, Trustees documented direct exposure of *Sargassum* to oil throughout the time surface oil was present (Figure 4.4-20). This evidence comes from observations of direct oiling during the spill response and observations of *Sargassum* within the oiling footprint (Powers 2011; Powers et al. 2013).

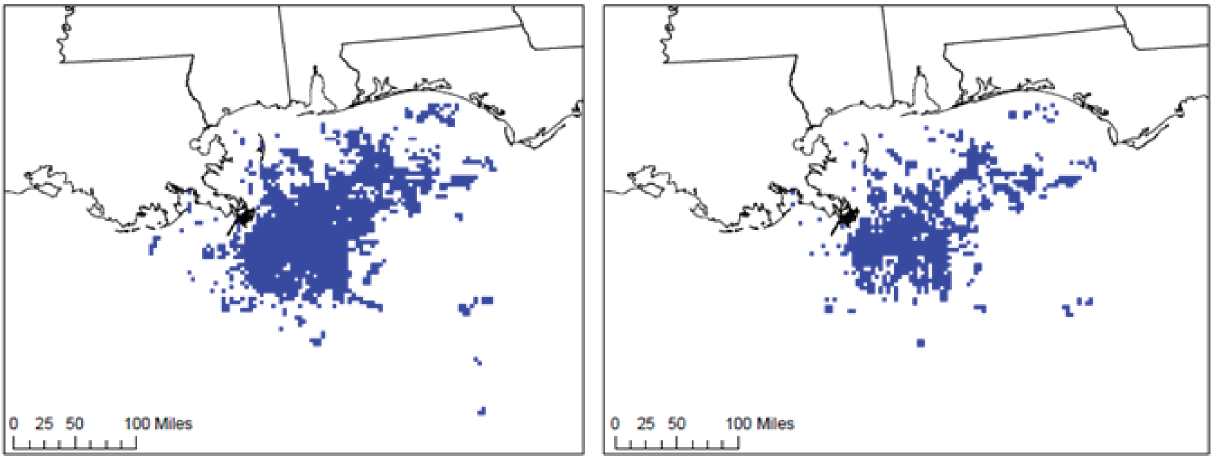
***Source:** Powers and Hernandez, NSF supported project, 2010.*

Figure 4.4-20. Example of oiled *Sargassum*.

Using the approach described in Section 4.4.2.3, the Trustees estimated a range for the area over which *Sargassum* was exposed to surface oil from the DWH spill of 26,025 to 45,825 square kilometers (Table 4.4-4). The lower and upper ends of this range are based on the area of the cumulative oil footprint with greater than 10 percent thick oil and greater than 5 percent thick oil, respectively. Figure 4.4-21 shows the lower and upper ranges of the areal extent of the cumulative surface oil footprint.

Table 4.4-4. Cumulative surface oil footprint by percent of area with thick oil.

Percent of Area with Thick Oil	Total (Square Kilometers)
> 5% thick oil	45,825
> 10% thick oil	26,025



Source: *Doiron et al. (2014).*

Figure 4.4-21. Cumulative areas of surface oiling displaying the total area in the northern Gulf of Mexico with at least 1 day of >5% thick oil (45,825 km^2; left) and >10% thick oil (26,025 km^2; right).

4.4.4 Injury Determination

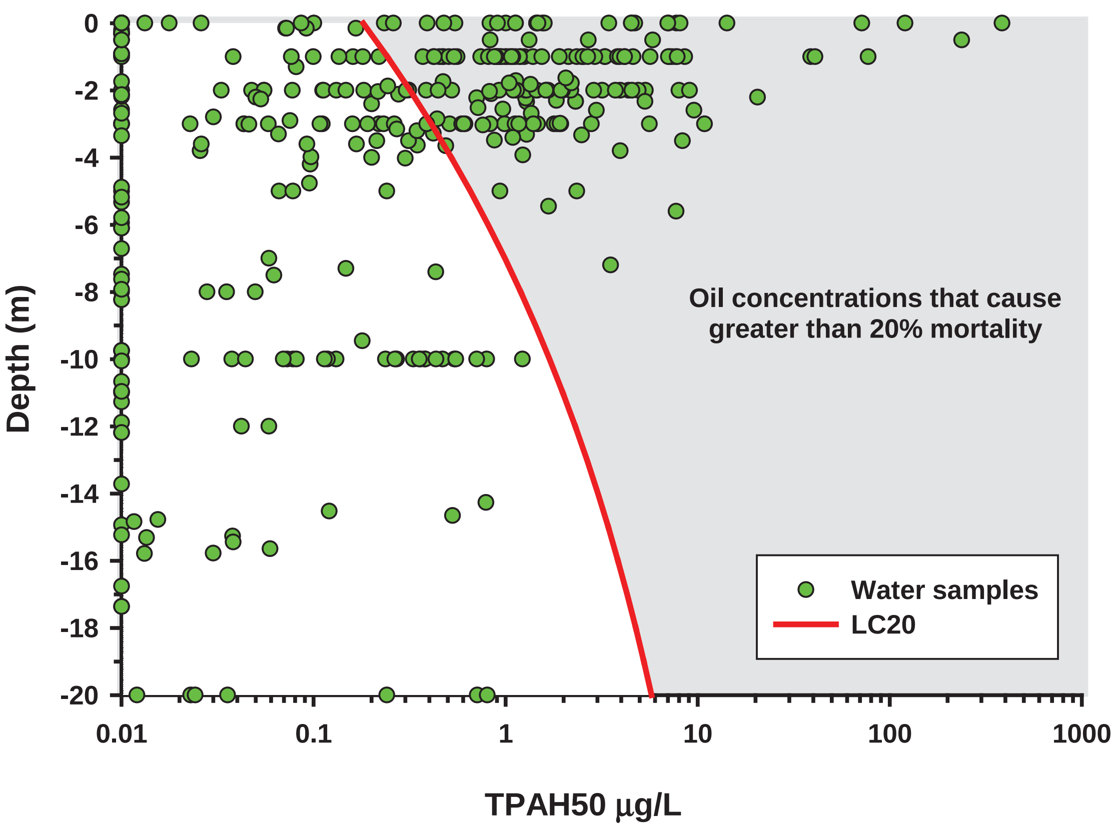
Key Points

- Water column concentrations measured in the Gulf of Mexico following the DWH oil spill exceeded levels known to cause lethal and sublethal effects to water column organisms.
- Early life stages of fish and invertebrates are particularly sensitive to oil exposure. Sunlight has been documented to magnify this effect.
- Field studies documented community-level and physiological injuries to water column resources, including trophic shifts, community structure shifts, reduced growth, impaired reproduction, and adverse health effects.

As presented earlier, the Trustees used NRDA empirical data, modeling, and additional studies from the scientific community to document DWH oil contamination throughout the Gulf water column and exposure of DWH oil to water column resources. As a next step, the Trustees used laboratory studies and field observations to understand potential effects of oil on water column organisms. The Trustees used representative species as key indicators of oil effects and applied an understanding of fundamental ecological relationships and processes to make reasonable scientific inferences about natural resources and services that were not explicitly studied. As discussed below, post-spill PAH concentrations measured in the northern Gulf water column exceeded levels known to cause lethal and sublethal effects among selected organisms. Field studies conducted in the Gulf of Mexico following the DWH oil spill also provide strong evidence of injuries to water column resources at both the species and community levels. The following sections describe the effects of oil on water column resources as documented in both laboratory studies (Section 4.4.4.1) and field observations (Section 4.4.4.2). These sections review studies funded through the NRDA and those reported by the scientific community.

4.4.4.1 Laboratory Studies

Toxicity studies conducted by the Trustees demonstrated that DWH oil mixed into the water and floating on the surface is toxic to early life stages of Gulf fish and invertebrates (Section 4.3, Toxicity). Additionally, the Trustees determined that exposure to UV light during or after exposure to DWH oil increases the toxicity by 10 to 100 times (Lay et al. 2015b). With exposure to an average amount of UV light present in the Gulf of Mexico during the spill, these toxic effects manifest over a relatively short timeframe (i.e., on the order of 24 hours). Concentrations of TPAH50 and exposure to UV light in the water column during the spill were sufficient to cause acute mortality to ichthyoplankton and zooplankton species. For example, based on the UV-adjusted estimate of toxicity for spotted seatrout at varying UV-levels with depth in the water column, many samples collected below or near the floating oil exceeded LC_{20} concentrations—or levels estimated to kill at least 20 percent of the population (Figure 4.4-22).



Source: Abt Associates; TPAH50 data obtained from DIVER.

Figure 4.4-22. This figure shows that many water samples collected during the spill were toxic to early life stage spotted seatrout. The figure compares TPAH50 concentrations in water samples collected at different depths during the spill (green dots) to the estimated LC_{20} values for spotted (speckled) seatrout with UV light attenuation values (red line). Non-detect samples were set to 0.01 µg/L TPAH50 in this illustration so that they would be visible on the log scale. All field samples in the gray shaded area represent acutely toxic concentrations of TPAH50 to ichthyoplankton. For more information, see Section 4.3 (Toxicity), Travers et al. (2015b), and Lay et al. (2015b).

In addition to acute mortality, laboratory studies have documented a range of adverse toxicological effects due to oil on fish and invertebrates across numerous biological endpoints, including reduced growth (Brewton et al. 2013; Brown-Peterson et al. 2011; Brown-Peterson et al. 2015b; Griffitt et al. 2012; Griffitt et al. 2013; Morris et al. 2015b), immune suppression (Ortell et al. 2015), reduced swim performance (Mager et al. 2014; Morris et al. 2015b), and impaired cardiovascular development (Incardona et al. 2014). Sublethal toxic effects can reduce an organism's health, fitness, and ability to reproduce and survive. See Section 4.3 (Toxicity) for a detailed discussion on the range of effects caused by exposure to DWH oil.

4.4.4.2 Field Observations

4.4.4.2.1 Fish and Crustaceans

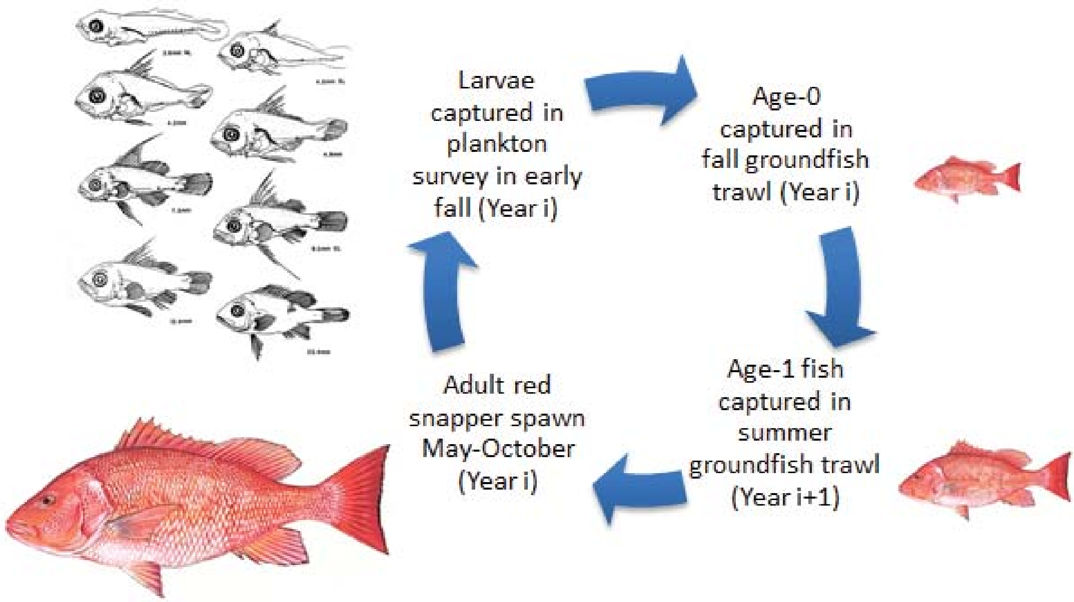
Reduced Recruitment

> **Red Snapper Life History**
>
> Adult red snapper spawn during the spring, summer, and fall months in the Gulf of Mexico (Moran 1988), releasing eggs into the water column. Larvae are then present in the water column for 15 to 30 days post-hatching. Age-0 red snapper typically are found in low-relief shell rubble and sand habitats (Patterson III et al. 2007; Patterson III et al. 2015). Some juvenile red snapper recruit to reefs with greater vertical relief at age 1, and the majority recruit to reefs by age 2 (Patterson III 2015; Patterson III et al. 2007).

Red snapper is a commercially and recreationally important species found in the Gulf of Mexico, with early life stages present in the water column and older individuals recruiting to natural and artificial reefs on the continental shelf (Patterson III et al. 2007). Due to its behavior to congregate around reef structures, red snapper are highly susceptible to fishing and are on the NMFS list of overfished stocks (NOAA 2015). The Gulf of Mexico red snapper stock assessment uses fisheries-independent and fisheries-dependent data to estimate the status of the stock relative to fishing and biomass benchmarks via stock assessment modeling; this stock assessment was updated through 2011 (SEDAR 2013). Although the stock assessment showed that the Gulf of Mexico red snapper population was rebuilding since the mid-2000s, the model predicted the lowest recruitment of age-0 red snapper in the eastern Gulf of Mexico in 2010 and 2011, compared to the past 20 years (A.G Pollack et al. 2012; SEDAR 2013; Tetzlaff & Gwinn 2015). To further investigate this finding and determine if the diminished recruitment was a result of the DWH oil spill, the Trustees analyzed fisheries-independent datasets across multiple gear types, habitat types, and size classes to examine red snapper abundance in the years following the DWH oil spill (Patterson III 2015; Tetzlaff & Gwinn 2015). Other field observations on the red snapper population, such as changes in trophic structure and reduced growth, are discussed in the sections below.

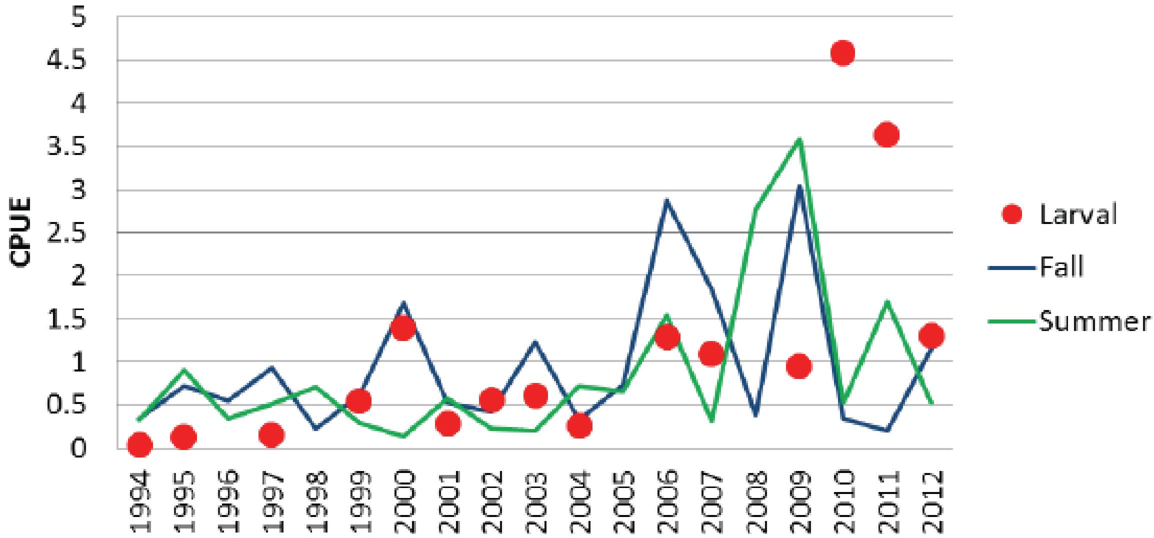
Building off the Gulf of Mexico red snapper stock assessment (A.G Pollack et al. 2012; A.G. Pollack et al. 2012; SEDAR 2013), the Trustees used SEAMAP fisheries-independent data and modeling to calculate abundance indexes of larval, age-0, and age-1 red snapper through 2012, with different surveys targeting specific size classes (Figure 4.4-23). Analyses of the SEAMAP early fall plankton surveys in 2010 and 2011 suggest high red snapper larval abundances in the eastern Gulf of Mexico water column during this time, as shown in Figure 4.4-24 (A.G Pollack et al. 2012; SEDAR 2013; Tetzlaff & Gwinn 2015). However, the SEAMAP fall groundfish surveys provide evidence of low abundances of red snapper in the eastern Gulf of Mexico in 2010 (2010 year class) and 2011 (2011 year class) (A.G. Pollack et al. 2012;

SEDAR 2013; Tetzlaff & Gwinn 2015). These results suggest that although high abundances of red snapper larvae were observed in the water column for the 2010 and 2011 year classes in early fall, these abundant larval populations did not translate into higher recruitment of age-0 fish in late fall for either the 2010 or 2011 year classes (Tetzlaff & Gwinn 2015). However, this trend of low abundance was not observed in the SEAMAP summer ground fish survey in 2011 and 2012 (predominately catching age-1 fish), indicating that the low age-0 abundances did not translate into low age-1 abundances for the same 2010 and 2011 year classes (Figure 4.4-24).



***Source**: From Tetzlaff and Gwinn (2015).*

Figure 4.4-23. Overview of SEAMAP fisheries surveys and red snapper life history. Red snapper typically spawn between May and October, releasing eggs into the water column. The SEAMAP early fall plankton survey samples the newly hatched larvae. The SEAMAP fall groundfish survey captures predominantly age-0 fish. The SEAMAP summer groundfish survey captures predominantly age-1 fish.



Source: *Tetzlaff and Gwinn (2015).*

Figure 4.4-24. Indices of red snapper recruitment in the Eastern Gulf of Mexico. Larval abundance indexes (red dots) are based on SEAMAP early fall plankton surveys. SEAMAP fall groundfish surveys (blue line) predominantly index age-0 fish abundance. SEAMAP summer groundfish surveys (green line) predominantly index age-1 fish abundance. High red snapper larvae abundances were observed in early fall 2010 and 2011 (red dots in grey highlight box); however, these abundant larval populations did not translate into higher recruitment of age-0 fish in late fall for either of these year classes (blue line in grey highlight box).

The observed decline in age-0 red snapper abundances could be explained by the DWH oil spill, impacting the survival of red snapper larvae, age-0 fish, or post-settlement red snapper on the shelf. However, alternative explanations could include poor larval settlement due to oceanographic environmental conditions or increased abundance of predators. Using a before-after-control-impact analysis, the Trustees investigated red snapper abundance before, during, and after the DWH oil spill in the impacted area (i.e., within the area of the Gulf of Mexico that was impacted by the DWH oil spill) and a control area (i.e., outside the area of the Gulf of Mexico that was impacted by DWH oil). A decline in age-0 fish was observed during the spill, relative to the time period before the spill (Tetzlaff & Gwinn 2015). However, this decline was not found to be significant and environmental variables, including water depth, salinity, and dissolved oxygen, explained significant amounts of variance in age-0 red snapper abundance (Tetzlaff & Gwinn 2015).

In addition to using SEAMAP survey data, the Trustees analyzed field data collected from natural and artificial reefs in the northern Gulf of Mexico to investigate whether red snapper recruitment to reefs was affected (Patterson III 2015). Since red snapper typically begin to recruit to reefs as age-1 fish, with the majority recruiting by age-2

Red Snapper Oil Exposure and Effects

Red snapper exposure to DWH oil is supported by carbon isotope ratios and relatively high concentrations of PAH metabolites in bile.

Field-collected data following the DWH oil spill observed changes in the red snapper community, including growth reductions, skin lesions, and shifts in diet.

(Patterson III 2015), a 1- to 2-year delay may occur before measurable oil spill impacts are seen in recruitment to reef populations. Analysis of ROV and vertical long line data from natural and artificial reefs in the northern Gulf of Mexico provided some observations of reduced abundances of the 2010-year class of red snapper in 2011 (age 1) and in 2012 (age 2) (Patterson III 2015). However, these findings were not consistent across age, gear type, and location, and not supported by other studies (Szedlmayer & Mudrak 2014).

In summary, these analyses provide limited evidence of diminished red snapper recruitment in the years following the oil spill (Patterson III 2015; Tetzlaff & Gwinn 2015). Reduced recruitment was observed in age-0 juvenile red snapper from the 2010 and 2011 year classes from the eastern Gulf of Mexico; however, environmental variables explained significant amounts of the variance. Some observations of reduced abundances of the 2010- and 2011-year classes were also detected as the cohort recruited to natural and artificial reefs as older fish; however, these signals are somewhat equivocal in the datasets examined. Although no strong trends were observed, it should be noted that statistical approaches for detecting trends in relative abundance are often limited by statistical power (Peterson et al. 2001) (Section 4.4.5.2). A very large suite of biotic and abiotic factors lead to a high degree of natural variation in estimates of annual abundance, both spatially and temporally, which poses challenges in identifying the effects from an event, such as an oil spill, from other environmental factors (Fodrie et al. 2014). Thus, although there is no strong support for DWH oil impacts on red snapper recruitment, the Trustees cannot rule out the possibility that recruitment was potentially affected by the spill.

Changes in Trophic Structure

Researchers have observed trophic level changes in the red snapper community following the DWH oil spill. Based on gut content and stable isotope analyses of red snapper collected on artificial and natural reef sites in the northern Gulf of Mexico from 2009 to 2011, researchers reported a significant shift in red snapper diet and trophic ecology after the DWH oil spill (Tarnecki 2014; Tarnecki & Patterson 2015). The researchers concluded that their results suggest both an increase in red snapper trophic position and a change from pelagic to benthic prey species (Tarnecki 2014; Tarnecki & Patterson 2015).

Changes in Community Structure

Researchers have reported effects of the DWH oil spill on fish community structure. For example, (Patterson III et al. 2015; Patterson III et al. 2014) observed shifts in reef fish communities beginning in summer 2010. The greatest changes were observed in small demersal fish, such as damselfish, cardinalfish, and wrasses, many of which declined in abundance by 100 percent following the DWH oil spill. Several species of large fishes, including snappers, jacks, and triggerfish, also declined in abundance up to 70 percent the year following the spill (Patterson III et al. 2014). By the fourth year post-spill, fish communities generally showed signs of resiliency, except for small demersal fish, which had persistently lower densities (Patterson III et al. 2015).

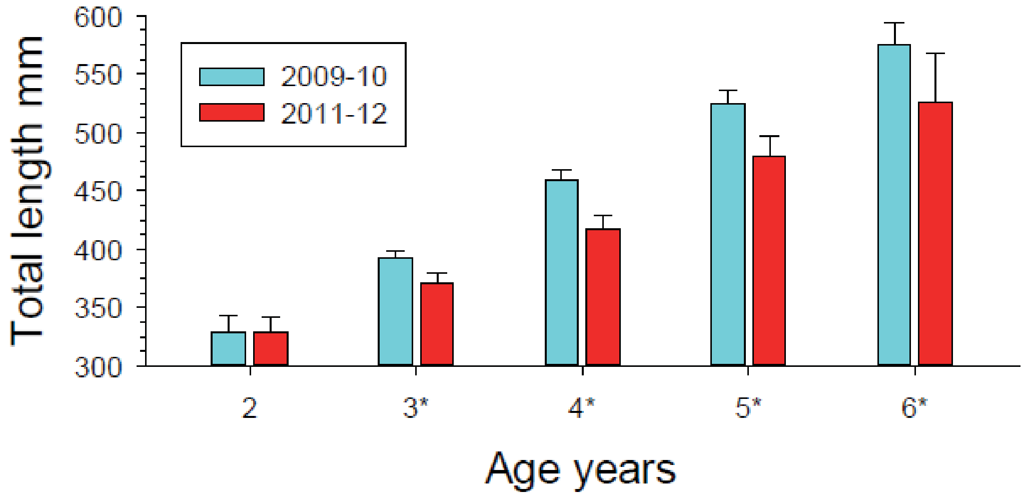
As a potentially confounding factor, increases in invasive lionfish have also been observed on reef sites in the northern Gulf of Mexico, with the highest densities of lionfish (*Pterois* spp.) reported on artificial reef sites in 2012 and 2013 (Dahl & Patterson III 2014). Notably, however, lionfish densities were not detected on natural reef sites in 2010, and greater than an order of magnitude lower densities of

lionfish were observed on natural reef sites (<0.05 fish per 100 square meters) compared to artificial reef sites (approximately 2 fish per 100 square meters) in 2011 (Dahl & Patterson III 2014). Based on these observations, the Trustees conclude that the lionfish invasion cannot solely explain the observed changes to the reef fish community on natural reef sites in the northern Gulf of Mexico following the DWH oil spill.

Reduced Growth

Researchers observed reduced growth rates and size at age for red snapper collected on reef sites following the DWH oil spill (Herdter 2014; Neese 2014; Patterson III 2015). Through analyzing red snapper otoliths collected in the northern Gulf of Mexico and West Florida Shelf, Herdter (2014) found a significant decline in fish growth corresponding with the timeframe of the DWH oil spill. Similarly, researchers observed significant decreases in size at age of red snapper sampled on reefs off the coast of Alabama and Florida (Neese 2014; Patterson III 2015). As shown in Figure 4.4-25, the length of red snapper sampled after the DWH oil spill (2011–2012) were significantly smaller than those of the same age collected before the spill (2009–2010). As discussed above and below, red snapper diet shifts (Tarnecki 2014; Tarnecki & Patterson 2015) and increased prevalence of lesions (Murawski et al. 2014) were observed following the DWH oil spill. These observations suggest that red snapper were under greater stress that may have negatively affected their growth rates in the years following the spill (Patterson III 2015). Researchers have also reported reduced size at age for tomtate (*Haemulon aurolineatum*), another reef fish, following the DWH oil spill (Norberg & Patterson 2014).

These field results are consistent with observations from laboratory studies and field experiments that have reported decreased growth rates for fish and crustaceans exposed to oil. For example, researchers held brown and white shrimp in field mesocosms in Barataria Bay, Louisiana, along shorelines that were impacted by the DWH oil spill (Rozas et al. 2014). The researchers reported growth rates for brown shrimp to be significantly lower at heavily oiled shorelines compared to those observed at very lightly oiled shorelines and shorelines with no oil (Rozas et al. 2014). Laboratory studies have also documented decreased growth rates of fish and shrimp exposed to oil-contaminated water or sediment (Brewton et al. 2013; Brown-Peterson et al. 2011; Brown-Peterson et al. 2015b; Griffitt et al. 2012; Griffitt et al. 2013; Morris et al. 2015b) (see Section 4.3, Toxicity, for more information).



Source: *Patterson III (2015).*

Figure 4.4-25. Red snapper size at age on reef sites in the north central Gulf of Mexico. Mean (95 percent confidence interval) size at age of red snapper sampled in the north central Gulf of Mexico before (2009–2010) versus after (2010–2012) the DWH oil spill as reported by Neese (2014) and Patterson III (2015). As shown in the figure, red snapper (ages 3–6) sampled after the DWH oil spill (2011–2012) were significantly smaller than those collected before the spill (2009–2010).

Impaired Reproduction

Researchers observed impaired reproductive parameters in spotted (also known as speckled) seatrout collected from Barataria Bay, Louisiana, and the Mississippi Gulf Coast 1 year following the spill, compared to historical data from the same location (Brown-Peterson et al. 2015a). For example, researchers documented both significantly lower gonad weights (relative to body weight) in females and significantly reduced spawning frequency, compared to pre-spill data (Brown-Peterson et al. 2015a).

Adverse Health Effects

Fish health may have also been impacted as a result of the DWH oil spill. For example, researchers and fishermen have reported an increased prevalence of skin lesions in red snapper and other fish species following the DWH oil spill (Burdeau 2012; Murawski et al. 2014; Pittman 2011). Consistent with the decreasing DWH oil exposure and decreasing concentration of PAH metabolites in red snapper bile over time, the overall frequency of lesions declined from 2011 to 2012 (Murawski et al. 2014). These findings are also supported by laboratory experiments exposing fish to a combination of oil and pathogenic bacteria (Ortell et al. 2015). These studies found that oil exposure impaired immune function of fish, increasing their susceptibility to infection, which led to increased death (likely due to pathogenic bacteria) and caused skin lesions in some fish (Ortell et al. 2015).

In addition, researchers found that 19 percent of red drum caught in Barataria Bay and near the Mississippi River Delta suffered from anemia (i.e., low numbers of red blood cells), while none of the fish caught at reference sites in Terrebonne Bay displayed signs of anemia (Harr et al. 2015). Fish collection sites in Terrebonne Bay were selected because the closest shorelines were classified in the no-oil-observed Shoreline Cleanup and Assessment Team (SCAT) category, while Barataria Bay and Mississippi River Delta sites were selected based on their classification in the heavy oiling SCAT category (Harr et al. 2015). In laboratory toxicity tests, oil caused low red blood cell counts in fish and birds (Section 4.3, Toxicity) (Bursian et al. 2015a; Bursian et al. 2015b; Dorr et al. 2015; Fallon et al. 2014; Harr et al. 2015; Ortell et al. 2015). Animals with reduced red blood cell counts are less able to transport oxygen throughout their body and, therefore, have less energy. As a result, organisms with anemia are at a competitive disadvantage in terms of catching prey, escaping predators, and other activities important for their fitness.

Physiological and genomic impacts were also observed in resident marsh fish species, as discussed in more detail in Section 4.3. Gulf killifish, a low trophic level forage fish collected from oiled sites in coastal Mississippi and Alabama, had gill damage and changes in gene expression associated with ion regulation, stress response, immune response, developmental abnormalities, and decreased reproductive success (Dubansky et al. 2013; Whitehead et al. 2012). Fish with gill damage are unable to uptake normal levels of oxygen, while the abnormal gene expression patterns reduce the organism's general fitness, because they spend more energy toward addressing these adverse effects (e.g., fighting off infections) and thus have less energy to put toward catching food and escaping predators.

Effects of Oil on Fish

Laboratory studies using DWH oil documented:

- Mortality to early life stages.
- Reduced growth.
- Immune suppression.
- Reduced swimming performance.
- Impaired cardiovascular development.

Post-DWH oil spill field studies observed:

- Reduced growth.
- Impaired reproduction.
- Skin lesions.
- Anemia.
- Trophic shifts.
- Community structure shifts.

4.4.4.2.2 Phytoplankton, Zooplankton, and Bacteria

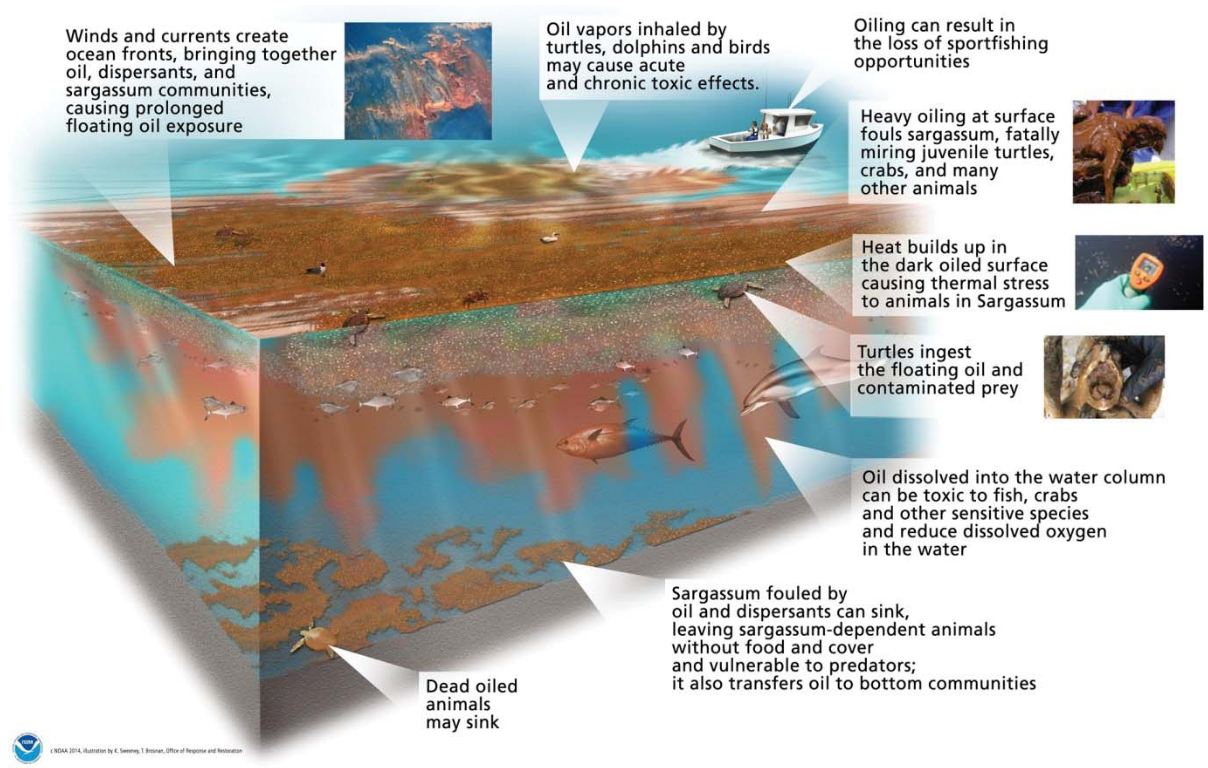
Field studies reported by the scientific community have documented changes in community composition for plankton and bacterial communities following the DWH oil spill. For example, researchers reported significant changes in the mesozooplankton community off the coast of Alabama during May and June 2010, compared to historical data during the same time period (Carassou et al. 2014). In addition, a shift in dominant bacteria was observed in the large subsurface plume (900–1,300 meters beneath the surface) following the DWH oil spill between March and August 2010 (Dubansky et al. 2013). Other studies reported altered community composition of bacteria in the plume compared to sites outside of the plume (Lu et al. 2012; Redmond & Valentine 2012; Yang et al. 2014) and stimulation of oil-degrading bacteria (Hazen et al. 2010).

Laboratory studies have also demonstrated oil directly affects phytoplankton and zooplankton. See Section 4.3 (Toxicity) for additional discussion.

4.4.4.2.3 Effects of Oil on *Sargassum*

Section 4.4.2.3 described the important role of *Sargassum* in the ecosystem and how it provides essential habitat to a wide array of fish, invertebrates, and other animals in the open ocean. When *Sargassum* becomes fouled by oil, it can no longer provide these ecosystem services. Scientific literature supports the conclusion that the physical coating of *Sargassum* with oil causes substantial, acute injury to *Sargassum* and that lower levels of oil likely inhibit or decrease growth (Powers 2012). Furthermore, oiled *Sargassum* harms the invertebrates, fish, and other animals (e.g., sea turtles and birds) found within it and nearby. This harm occurs through physical fouling and direct toxicity from exposure to oil, and potentially by reducing the availability of dissolved oxygen.

In addition, the exposure of *Sargassum* to both oil and dispersant can cause *Sargassum* to sink to the ocean floor, decreasing the area of this important habitat. The sinking of oiled *Sargassum* could serve as an additional pathway of oil exposure to benthic flora and fauna (Powers et al. 2013). Figure 4.4-26 shows the myriad effects of oil exposure on *Sargassum.*



Source: *Kate Sweeney for NOAA.*

Figure 4.4-26. Illustration of the potential impacts of oiled *Sargassum* and associated biota in the water column.

4.4.4.3 Summary

Post-spill water column concentrations measured in the northern Gulf of Mexico exceeded levels that are known to cause lethal and sublethal effects to aquatic organisms, providing evidence of injuries to water column resources. Community and physiological effects were also recorded during field observations following the DWH oil spill. Notably, growth reductions (Herdter 2014; Neese 2014;

Patterson III 2015), shifts in diet (Tarnecki 2014; Tarnecki & Patterson 2015), and increased prevalence of lesions (Murawski et al. 2014) were observed in red snapper collected from the northern Gulf of Mexico; reef fish populations displayed shifts in community structure (Patterson III et al. 2015; Patterson III et al. 2014); and impaired reproduction (Brown-Peterson et al. 2015a) and anemia (Harr et al. 2015) were observed in spotted seatrout and red drum, respectively. Many of these endpoints were also observed in laboratory experiments studying the effects of oil exposure. Additional biological endpoints observed in the laboratory include immune suppression, reduced swimming performance, and impaired cardiovascular development (Section 4.3, Toxicity). Sublethal toxic effects can reduce organisms' health, fitness, and ability to reproduce and survive. For example, oil exposure may interfere with organisms' ability to respond to suboptimal environmental conditions, and the combined effects of naturally encountered stressors (e.g., salinity, hypoxia, pathogens) may contribute to impacts on species fitness as well as to populations and communities (Whitehead 2013).

4.4.5 Injury Quantification

Key Points

- The Trustees used mortality to early life stages of fish and planktonic invertebrates exposed to oil in the surface slick, the subsurface mixed zone, the rising cone, and the deep plume of oil to quantify the number of organisms killed as a direct result of oil exposure.
- The Trustees estimated that the total number of larval fish and invertebrates killed was 2 to 5 trillion and 37 to 68 trillion, respectively. The range of survival for fish larvae to live past 1 year of age ranges from one in a thousand to 1 in 5 million (French McCay et al. 2015d). This translates into a loss of millions to billions of fish that would have reached age 1.
- The estimated total number of fish and planktonic invertebrates killed in estuarine waters was between 0.4 and 1 billion and between 2 and 6 trillion, respectively. The Trustees also estimated the lost growth that some of the killed organisms would have undergone if they had lived their normal lifespan.
- Analyses of long-term fisheries-independent datasets did not detect significant changes to fisheries populations. However, due to the inherent variability in fisheries datasets, the Trustees cannot rule out the possibility for population-level effects.
- Analysis of *Sargassum* found that exposure to oil may have caused the loss of up to 23 percent of this habitat. The total loss of *Sargassum*, including foregone area from lost growth, is 11,100 square kilometers.

As presented in Section 4.4.2, Approach to the Assessment, the Trustees used NRDA empirical data, modeling, and additional studies from the scientific community to document 1) DWH oil contamination throughout the Gulf water column, 2) exposure of DWH oil to water column resources, and 3) lethal and sublethal effects of DWH oil on aquatic organisms. As a next step, the Trustees quantified injuries to water column resources as a result of the DWH oil spill. The integrated water column resource analysis, including the injury quantification of fish and planktonic invertebrate species, is presented in Section

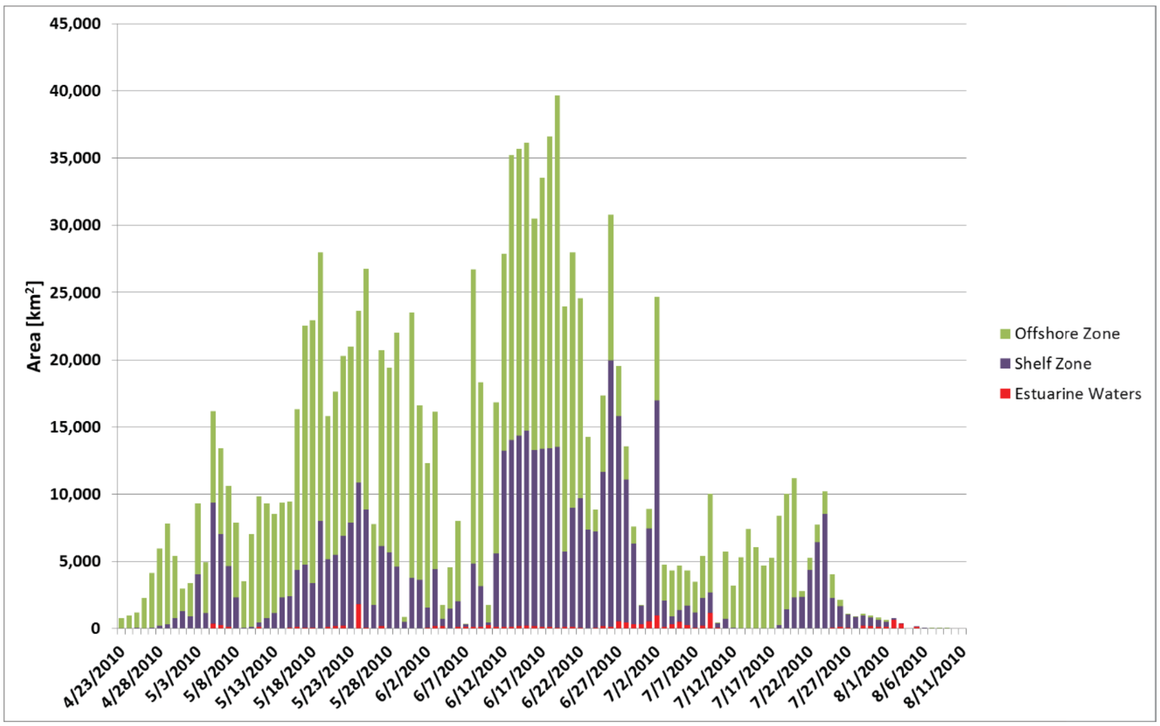
4.4.5.1. Analyses of long-term fisheries-independent datasets are presented in Section 4.4.5.2. The *Sargassum* injury quantification is presented in Section 4.4.5.3.

4.4.5.1 Integrated Water Column Resource Analysis

This section presents the Trustees' integrated water column resource analysis to quantify injuries to resources found within the estuarine, shelf, and offshore water column. The quantification of injuries is based on the mortality of water column resources as a result of the DWH oil spill. Separate analyses were performed for the surface slick and subsurface mixed zone for the offshore, shelf, and estuarine areas (Section 4.4.5.1.1) and for the rising oil and deep plume of oil at depth (Section a).

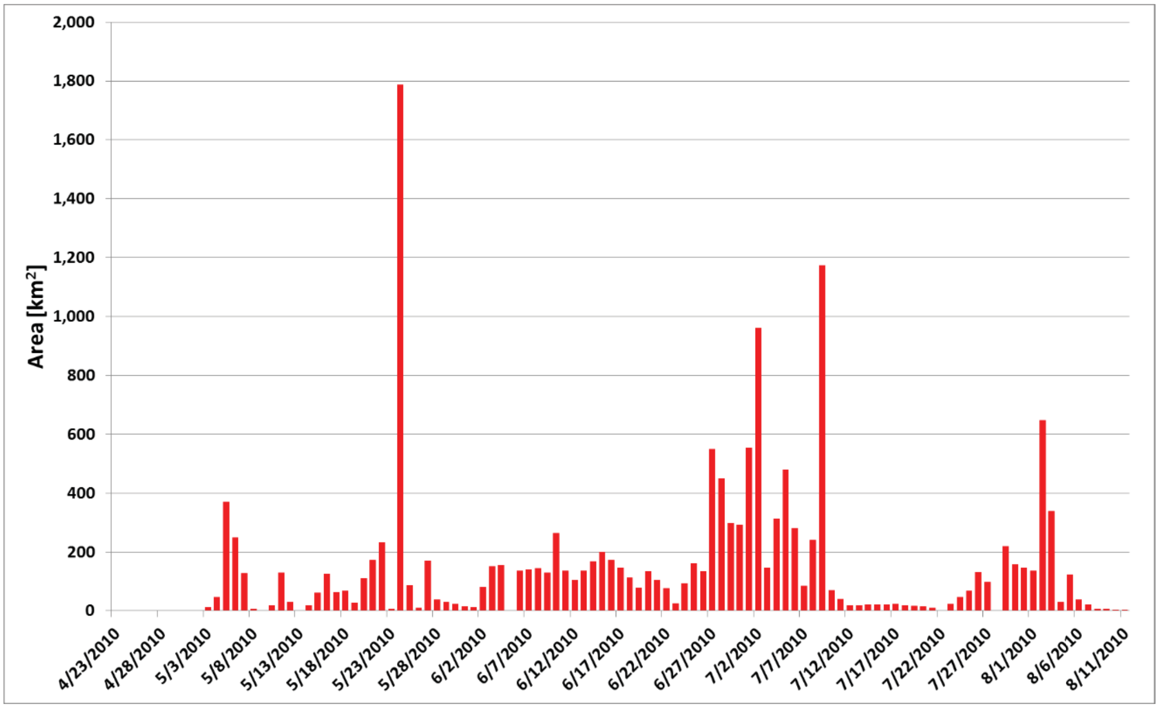
4.4.5.1.1 Surface Slick and Subsurface Mixed Zone

The SAR images demonstrate that oil was present on the water in the Gulf of Mexico from at least April 23, 2010, until August 11, 2010. Figure 4.4-27 plots the areal extent of surface oil detected in the offshore, shelf, and estuarine areas by day; Figure 4.4-28 plots the same information for estuarine waters only.



Source: Travers et al. (2015b).

Figure 4.4-27. Estimated areal extent of surface oil during the DWH spill in offshore, shelf, and estuarine waters.

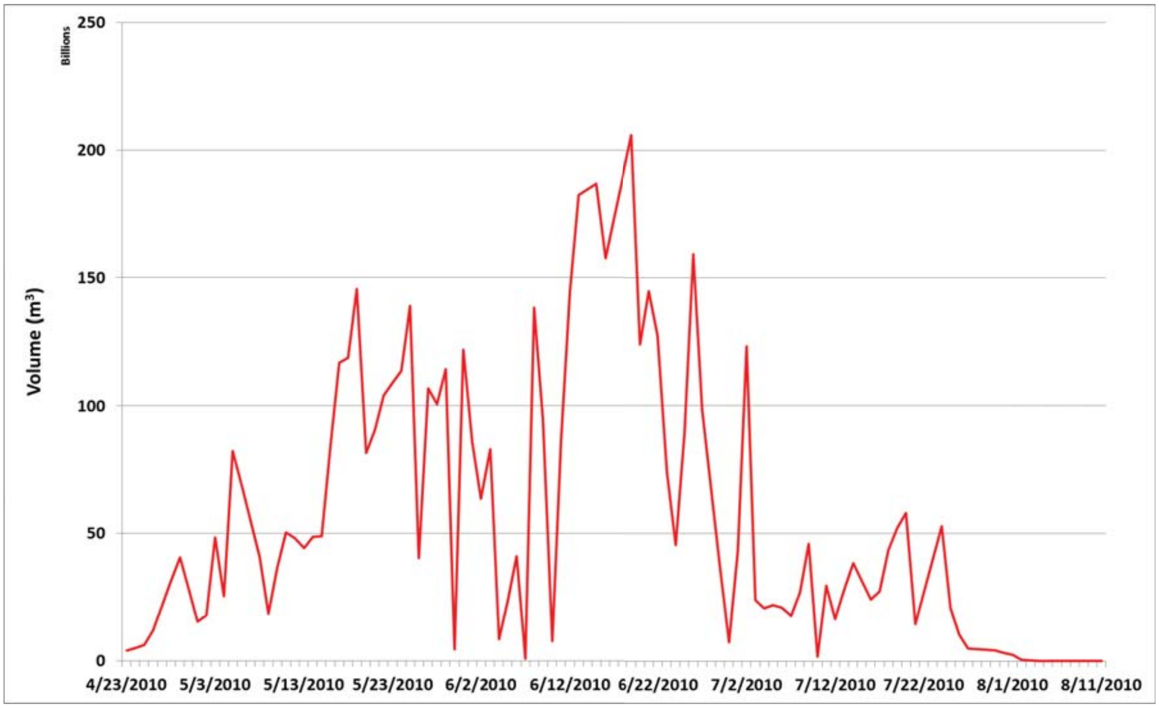


***Source**: Travers et al. (2015b).*

Figure 4.4-28. Estimated areal extent of surface oil during the DWH spill in estuarine waters.

Biota were exposed to oil in the upper water column on a daily basis over the 113 days that oil was present on the water surface. To account for this daily exposure, the daily areal extent of surface oil was summed for the duration of the spill. Across all surface waters, an estimated 1.23 million square kilometer-days (475,000 square mile-days) were exposed to floating oil. The potentially affected volume of water under the floating oil for each day of the spill was calculated assuming a depth of 20 meters (65 feet) for shelf and offshore areas and an estimated 26 percent of that water under floating oil exceeded 0.5 µg/L (Travers et al. 2015a). Figure 4.4-29 shows the total volume of water over each day; it shows the maximum volume of water potentially affected by the spill on 1 day is 210 billion cubic meters on June 19, 2010. The average daily volume of water exceeding a TPAH50 concentration of 0.5 µg/L is 57 billion cubic meters. To provide some context, the average annual discharge from the Mississippi River at New Orleans is 600,000 cubic feet per second (NPS 2015) or 1.5 billion cubic meters per day. Thus, the volume of water exceeding a TPAH50 concentration of 0.5 µg/L in the upper mixed layer was approximately 40 times the average daily discharge (based on average annual discharge) in the Mississippi River.

In addition, because oil was on the surface of the Gulf of Mexico for 113 days, the daily exposure can be added for each day of the spill to describe the cumulative affected volume in gallon-days. Summing the volume of water estimated to exceed 0.5 µg/L every day for the upper water column offshore and shelf areas, 6.3 trillion-cubic-meter days of water were potentially affected by DWH oil.



Source: *Travers et al. (2015b).*

Figure 4.4-29. Estimated cubic meters of water affected by surface oil slicks from the DWH spill. The red line represents the estimated volume of water in billions of cubic meters exceeding a TPAH50 concentration of 0.5 µg/L from April 23 to August 11, 2010.

Based on the empirical chemistry data, the Trustees estimated that 26 percent of the water at depths between 0 and 20 meters in the offshore and shelf zones had TPAH50 concentrations greater than 0.5 µg/L (Travers et al. 2015a), which is sufficiently high to harm sensitive life stages of biota in the presence of UV light (Section 4.3, Toxicity).

Using the methods described, the Trustees estimated 4–6 percent mortality for invertebrates offshore and 21–45 percent mortality for larval fish offshore (Table 4.4-5). The total number of larval fish and invertebrates killed in the upper 20 meters of the offshore surface waters was estimated to be between 2 and 5 trillion and 37 and 68 trillion, respectively. The fish larvae killed included 30 to 400 billion herring (menhaden and relatives), 80 to 500 billion anchovies, 20 to 100 billion snappers, and 70 to 400 billion tunas and mackerels. Detailed calculations, tabulating results by species, are in the RPS Applied Science Associates (ASA) Technical Report (French McCay et al. 2015d).

Note that not all larval fish are expected to survive past a year. Depending on the species, the range in survival, from the larval size captured in survey nets to 1 year of age, is from approximately one in a thousand to one in 5 million. Looking across all species, this gives a vast range, from millions to billions, of fish that would have reached a year old if they had not been killed by the spill. Additionally, the larval fish that were killed but would not have survived to age 1 are a significant loss. Section 4.4.1.2 explains that larval fish are an important component of the plankton community that form the base of the aquatic food web and provide an energy source for other components of the ecosystem.

Table 4.4-5. Estimated percent mortality from oil exposure.

	Less Sensitive Species	More Sensitive Species
Offshore	**Percent of total in upper 0–20 meters of water column**	
Eggs and larval fish	21%	45%
Invertebrates	4%	6%
Estuarine	**Percent of total 2.5 meters of water column**	
Eggs and larval fish	4%	6%
Invertebrates	5%	5%

For estuarine waters, the Trustees estimate 16,000 square kilometer-days (6,200 square mile-days) of the total estuarine surface area were exposed to floating oil for the duration of the spill. The volume of water affected by the floating surface oil in estuaries, assuming UV light penetrates to a depth of 0.2 meters (0.6 feet) in the turbid estuarine waters, was 3 billion cubic-meter days. Based on a range of sensitivities, the Trustees estimate 4 to 6 percent mortality for larval fish in the estuarine waters and the total number of larval fish killed is 0.4 to 1 billion. The estimated larval invertebrate and small zooplankton (French McCay et al. 2015d) mortality of 5 percent in estuarine waters results in 2 to 6 trillion planktonic invertebrates killed. Table 4.4-6 summarizes injury quantification metrics for the surface and subsurface mixed zone in the offshore, shelf, and estuarine areas (French McCay et al. 2015d; Travers et al. 2015b).

Table 4.4-6. Metrics used by Trustees for upper water column injury quantification.

Metric	Quantification (with Range Where Applicable)
Area covered by surface oil slick	
Maximum daily areal extent of oil on surface during the spill (offshore, shelf, and estuarine)	39,700 km^2 (15,300 mi^2) on June 19, 2010
Average daily areal extent of oil on surface during the spill (offshore, shelf, and estuarine)	11,100 km^2 (4,300 mi^2)
Cumulative areal extent of oil on surface during the spill (offshore, shelf, and estuarine)	112,000 km^2 (43,300 mi^2)
Area of oil on surface for duration of the spill, sum of daily footprints (offshore, shelf, and estuarine)	1,229,000 km^2-days (475,000 mi^2-days) [a]
Area of oil on estuarine waters for duration of spill, sum of daily footprints	15,600 km^2-days (6,000 mi^2-days)
Volume of water affected by surface oil slick	
Maximum daily volume of water under the slick exceeding TPAH50 of 0.5 µg/L (offshore/shelf)	2.1×10^{11} (210 billion) m^3 on June 19, 2010
Average daily volume of water under the slick exceeding TPAH50 of 0.5 µg/L (offshore/shelf)	5.7×10^{10} (57 billion) m^3
Volume of water under the slick exceeding TPAH50 of 0.5 µg/L, sum of daily volumes (offshore/shelf)	6.3×10^{12} (6.3 trillion) m^3-days[b]
Average daily volume of affected estuarine waters	3.1×10^{7} (31 million) m^3
Affected volume of estuarine waters, sum of daily volumes	3.1×10^{9} (3 billion) m^3-days

Metric	Quantification (with Range Where Applicable)
Percent mortality	
% invertebrate mortality in 0–20 m (offshore)	4–6%
% egg and larval mortality in 0–20 m (offshore)	21–45%
% invertebrate mortality, average depth 2.5 m (estuaries)	5%
% egg and larval mortality, average depth 2.5 m (estuaries)	4–6%
Biota directly killed	
Direct kill: Total number planktonic invertebrates killed (offshore)	37x10^{12} to 68x10^{12} (37 to 68 trillion)
Direct kill: Total number larval fish killed (offshore)	2x10^{12} to 6x10^{12} (2 to 5 trillion)
Direct kill: Total number planktonic invertebrates killed (estuaries)	2x10^{12} to 6x10^{12} (2 to 6 trillion)
Direct kill: Total number larval fish killed (estuaries)	4x10^{8} to 1x10^{9} (0.4 to 1 billion)

[a] A km^2-day is a compound unit that means 1 square kilometer for one day, in any combination of area and time. For example, 100,000 km^2-days could mean 1,000 km^2 for 100 days, 10,000 km^2 for 10 days, or 100,000 km^2 for 1 day.

[b] An m^3-day is a compound unit that means 1 cubic meter for 1 day, in any combination of area and time. For example, 100,000 m^3-days could mean 1,000 m^3 for 100 days, 10,000 m^3 for 10 days, or 100,000 m^3 for 1 day.

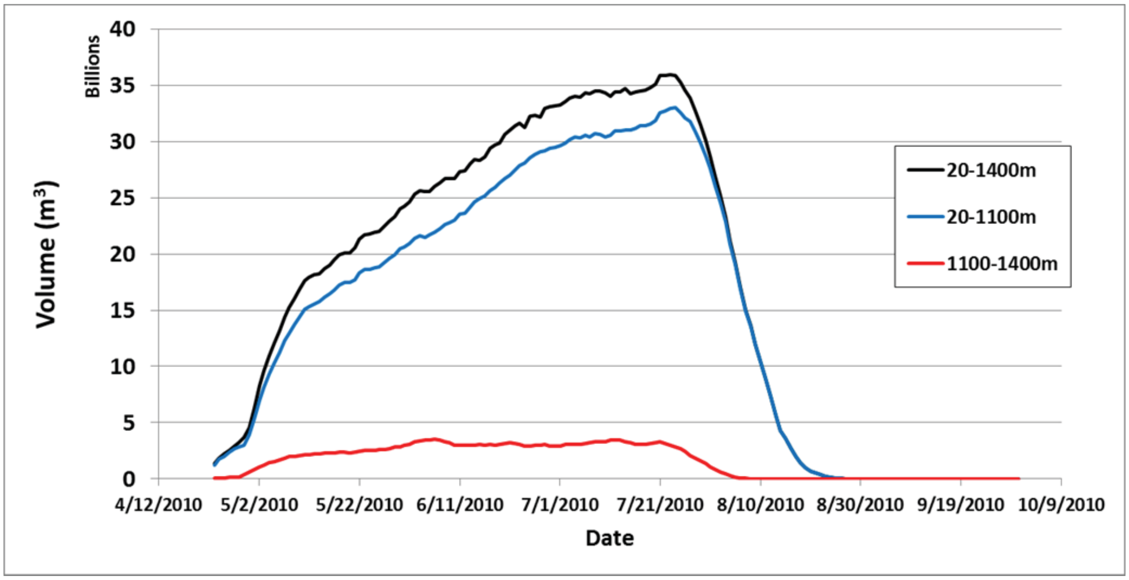
4.4.5.1.2 Rising Oil and Deep Plume of Oil at Depth

The model results provide a daily estimate of TPAH50 concentration distributions at depth. Table 4.4-7 summarizes the maximum daily volume of water with TPAH50 concentrations greater than 0.5 µg/L for the three depth zones.

Table 4.4-7. Model results for volume of deep water exceeding 0.5 µg/L TPAH50 and maximum TPAH50 concentration.

Portion	Depth Range		Maximum over time			Cumulative volume	
	Meters	Feet	Max Conc. (µg/L)	Volume (m^3)	Vol (gal)	m^3-days	gal-days
Cone	20–1,100	66–3,609	217	3.3x10^{10} (33 billion)	8.7x10^{12} (8.7 trillion)	2.6x10^{12} (2.6 trillion)	6.5x10^{14} (650 trillion)
Deep Plume	1,100–1,400	3,609–4,600	872	3.5x10^{9} (3.5 billion)	9.3x10^{11} (930 billion)	2.6x10^{11} (260 billion)	6.7x10^{13} (67 trillion)
Total	20–1,400	66–4,600	872	3.5x10^{10} (35 billion)	9.5x10^{12} (9.5 trillion)	2.7x10^{12} (2.7 trillion)	7.2x10^{14} (720 trillion)

Figure 4.4-30 shows the result of the modeled daily water volumes with TPAH50 concentrations greater than 0.5 µg/L in the depth of the rising cone and the deep plume for the duration of the oil release. The total cumulative volume of water exceeding this concentration was calculated by adding the volume for each day over the spill. The maximum volume was estimated at 35 billion cubic meters and the cumulative volume was 2.7 trillion cubic meter-days.



Source: *French McCay et al. (2015c).*

Figure 4.4-30. Daily volume of deep water with TPAH50 concentrations greater than 0.5 µg/L for oil released between April 22 and July 15, 2010. The lines represent the volume of water, in billions of cubic meters, for different water column depth zones. The rising cone (blue line) represents water depths up to 1,100 meters, and the deep plume (red line) represents depths between 1,100 and 1,400 meters beneath the surface. The black line is the sum of the total volume contributions from the two different subsurface zones.

The Trustees estimate the total number of larval fish killed in the deep water offshore is between 86 million and 26 billion and the total number of invertebrates killed is between 10 million and 7 billion (Table 4.4-8). The invertebrate life stages that were captured by the sampling gears were used to estimate baseline densities. They were also assessed in the injury quantification and include: microzooplankton that spend their entire life in the plankton (e.g., copepods, amphipods, mysids, krill), planktonic larval stages of benthic invertebrates (e.g., worms, barnacles, anemones, mantis shrimp), and planktonic early life history (primarily larval) stages of larger invertebrates (e.g., shrimp, crabs, lobsters, jellyfish, comb jellies, cephalopods, sea slugs, tunicates).

Table 4.4-8. Metrics used by Trustees for deep water injury quantification.

Metric	Quantification
Direct kill: Total number invertebrates killed (offshore)	$1x10^7$ to $7x10^9$ (10 million to 7 billion)
Direct kill: Total number larval fish killed (offshore)	$8.6x10^7$ to $2.6x10^{10}$ (86 million to 26 billion)

Direct Kill Estimate Considerations

The abundance estimates for juvenile fish and invertebrates throughout different water column areas are likely underestimates based on the inefficiency of the nets being used to estimate abundance (Johnson & Morse 1994; Morse 1989; Somerton & Kobayashi 1989) and the small volume of samples over a vast area. The nets used to capture fish larvae and invertebrates are not 100 percent efficient with some larger larvae avoiding the nets and smaller larvae potentially going through the nets' mesh. In addition, net samples were used in areas that do not include *Sargassum*, where the densities of some

fish larvae and invertebrates are higher. By applying these lower abundance estimates, the number of fish and invertebrates estimated to be killed would also be an underestimate.

Despite the fact that the number of fish and invertebrates killed may be considered an underestimate, we can evaluate minimal and maximal impacts of the spill on fish larvae by considering the percentage of fish larvae that overlapped with oil compared to the entire U.S. Gulf of Mexico Exclusive Economic Zone (EEZ). By using this approach and considering larval densities as an index instead of an absolute value, for the species investigated the total percent overlap with floating oil ranged from approximately 0.1 percent to 7.5 percent of the larvae spawned across the entire EEZ during the spill (Quinlan et al. 2015). Further considering the toxicity under the footprint yields an impact from 0.05 percent to 3.38 percent of the total spawn during the spill.

Though this discussion presented impact in terms of percentages of the entire EEZ, it must be noted that impacts could easily be much more pronounced and that localized impacts may be particularly important. If, rather than considering the entire EEZ, the analyses considered only high quality habitat or some reduced area, the percentages impacted would be higher. Additionally, production in some areas may be critically important for some species. There is a vast literature on connectance in larval fish ecology and the importance of spawning in the correct time and place (Cowen et al. 2007; Cowen & Sponaugle 2009; Paris & Cowen 2004; Quinlan et al. 1999). Injury to areas that produce fish that settle elsewhere could mean that the net impact was larger and more nuanced than depicted in these analyses.

4.4.5.1.3 Production Foregone

Quantification of production foregone is presented for example species in Table 4.4-9. Production foregone was only calculated for selected species—those for which the Trustees determined that the needed vital rates were reliable (i.e., for species well-studied by fisheries managers). Production foregone totals across all species affected by the spill were not calculated or assessed.

The examples shown in Table 4.4-9 serve to illustrate that the weight of larvae killed is only a small portion of the impact to the species and ecosystem, as the larvae would have grown and been predated over their natural lifespan. The direct kill numbers in the table are the weights of larvae killed, whereas production foregone numbers are the weight gains that they would have undergone if not killed by the spill. For some species of fish that grow very large, such as amberjack, large tunas, and mahi-mahi, growth after the larval stage is very rapid and the production foregone represents the majority of the biomass loss. On the other hand, small fish (e.g., spot, anchovies) do not grow as rapidly and their mortality rates are much higher, so production foregone is of similar magnitude to the weight of the directly killed larvae. Results for these and other species may be found in the RPS ASA Technical Report (French McCay et al. 2015d).

Table 4.4-9. Production foregone calculations for example fish and invertebrate species in the offshore, shelf, and estuarine waters.

Species	Direct Kill #'s	Direct Kill (kg)	Production Foregone (kg)	Total Injury (kg)
Red snapper (*Lutjanus campenchanus*)	2×10^9 – 7×10^9 (2 billion to 7 billion)	8×10^2 – 3×10^3 (800 to 3 thousand)	5×10^4 – 2×10^5 (50 thousand to 200 thousand)	5×10^4 – 2×10^5 (50 thousand to 200 thousand)
Seatrout (*Cynosicon* spp.)	2×10^{10} – 1×10^{11} (20 billion to 100 billion)	1×10^3 – 7×10^3 (1 thousand to 7 thousand)	8×10^3 – 5×10^4 (8 thousand to 50 thousand)	9×10^3 – 6×10^4 (9 thousand to 60 thousand)
Spot (*Leiostomus xanthurus*)	4×10^8 – 1×10^{10} (400 million to 10 billion)	2×10^1 – 5×10^2 (20 to 500)	3×10^1 – 7×10^2 (30 to 700)	5×10^1 – 1×10^3 (50 to 1 thousand)
Atlantic croaker	1×10^5 – 6×10^9 (100 thousand to 6 billion)	5×10^{-3} – 3×10^2 (5 thousandths to 300)	2×10^{-2} – 8×10^2 (2 hundredths to 800)	3×10^{-2} – 1×10^3 (3 hundredths to 1 thousand)
Spanish mackerel (*Scomberomorus maculatus*)	3×10^9 – 3×10^{10} (3 billion to 30 billion)	3×10^2 – 2×10^3 (300 to 2 thousand)	4×10^2 – 4×10^3 (400 to 4 thousand)	7×10^2 – 6×10^3 (700 to 6 thousand)
Amberjack (*Seriola* spp.)	2×10^8 – 3×10^{10} (200 million to 30 billion)	2×10^1 – 7×10^2 (20 to 700)	6×10^3 – 2×10^5 (6 thousand to 200 thousand)	6×10^3 – 2×10^5 (6 thousand to 200 thousand)
Large tunas (*Thunnus* spp.)	2×10^{10} – 1×10^{11} (20 billion to 100 billion)	2×10^3 – 8×10^3 (2 thousand to 8 thousand)	1×10^6 – 4×10^6 (1 million to 4 million)	1×10^6 – 4×10^6 (1 million to 4 million)
Mahi-mahi (*Coryphaena* spp.)	2×10^8 – 4×10^9 (200 million to 4 billion)	4×10^1 – 8×10^2 (40 to 800)	8×10^4 – 2×10^6 (80 thousand to 2 million)	8×10^4 – 2×10^6 (80 thousand to 2 million)
Anchovies (Engraulidae)	8×10^{10} – 7×10^{11} (80 billion to 700 billion)	4×10^4 – 2×10^5 (40 thousand to 200 thousand)	6×10^4 – 4×10^5 (60 thousand to 400 thousand)	1×10^5 – 6×10^5 (100 thousand to 600 thousand)
Gulf shrimp (Penaeids & similar)	2×10^{11} – 5×10^{11} (200 billion to 500 billion)	3×10^3 – 1×10^4 (3 thousand to 40 thousand)	2×10^5 – 9×10^5 (200 thousand to 900 thousand)	2×10^5 – 9×10^5 (200 thousand to 900 thousand)
Blue crabs (*Callinectes* spp.)	2×10^9 – 1×10^{10} (2 billion to 10 billion)	2×10^2 – 1×10^3 (200 to 1 thousand)	1×10^2 – 7×10^2 (100 to 700)	3×10^2 – 2×10^3 (300 to 2 thousand)

4.4.5.2 Fisheries Analysis

NOAA's NWFSC analyzed fisheries-independent survey data to examine changes in fish and invertebrate populations before and after the DWH oil spill. The analysis of the SEAMAP data series did not detect any major or unusual changes in CPUE in pre- or post-spill periods, although there was evidence of modest post-spill decreases in areas west of the Mississippi River Delta and concurrent modest increases in areas east of the Delta. Similarly, analyses of LDWF data did not detect any widespread or unusual changes in CPUE in pre- or post-spill periods.

Although no substantial or widespread changes in fisheries populations were detected, the Trustees cannot rule out the possibility that fisheries were impacted at a population level. Estimates of population abundance take several years to complete and verify, making these difficult to evaluate for a large-scale event, such as an oil spill. Changes in life history features, such as size at age structure, growth rates, liver function, and condition are immediate and better indicators of a stress event.

In addition, statistical approaches for detecting trends in relative abundance are often limited by the statistical power to detect changes. A very large suite of biotic and abiotic factors lead to a high degree of natural variation in estimates of annual abundance, even in the absence of a major impacting event such as an oil spill. The effects of such an impact on fish abundance, even though it may be substantial, can be statistically undetectable unless the magnitude of the effect is large enough to exceed the degree of natural variation. When statistical power is limited, it can be increased by increasing sample sizes or by reducing the degree of variation in the sampling process. However, for practical reasons (e.g., the historical record of fish abundance is already completed and not specifically designed for injury assessment), neither of these tactics is an available option in this injury assessment.

4.4.5.3 *Sargassum* Injury Quantification

The Trustees quantified injury related to *Sargassum* in two ways: 1) area of *Sargassum* oiled and 2) percent of *Sargassum* area foregone due to lost growth.

4.4.5.3.1 Area of Oiled *Sargassum*

Based on an analysis of satellite and low-altitude aerial imagery (described in Section 4.4.2.3), the Trustees determined that 2.8 percent of the northern Gulf of Mexico was covered by *Sargassum* during the period of the spill (95 percent confidence interval ranging from 1.8 to 3.8 percent). Multiplying these percent cover estimates by the area of surface oiling values in Section 4.4.3.3, we produced the area of *Sargassum* oiled by the DWH spill (Table 4.4-10). The total amount of *Sargassum* oiled ranges from 843 to 1,749 square kilometers within areas where the surface was covered by greater than 5 percent thick oil. This includes 479 to 993 square kilometers within areas where coverage was greater than 10 percent thick oil. Overall, 23 percent of the *Sargassum* in the northern Gulf of Mexico was lost due to co-location with ocean surface areas with greater than 5 percent thick oil, and 13 percent of the *Sargassum* was lost due to co-location with ocean surface areas with greater than 10 percent thick oil.

Table 4.4-10. Area of *Sargassum* within oiling footprint (km^2).

% Thick Oil	Lower Bound	Central Estimate	Upper Bound
> 5%	843	1,296	1,749
> 10%	479	736	993

4.4.5.3.2 *Sargassum* Area Foregone

An additional measure of *Sargassum* injury is the surface area foregone due to lost growth caused by oil exposure. As *Sargassum* moves across the northern Gulf of Mexico, it grows at a rate of 4 percent per day (LaPointe 1986; as cited in Powers 2012). Therefore, the Trustees were able to calculate ranges of surface area foregone of 4,524 to 9,392 square kilometers for the greater than 5 percent thick oil

footprint with a subset of 2,569 to 5,334 square kilometers for the greater than 10 percent thick oil footprint (Table 4.4-11).

Table 4.4-11. *Sargassum* surface area foregone (km^2).

% Thick Oil	Lower Bound	Central Estimate	Upper Bound
> 5%	4,524	6,958	9,392
> 10%	2,569	3,952	5,334

Sargassum represents a rich environment in the open ocean that supports a high density of fauna, ranging from fish larvae and invertebrates that live on it, to the larger fish, sea turtles, and sea birds that rely on it for foraging and protection from predators. Therefore the oiling of this *Sargassum* and the loss of *Sargassum* area due to oiling and lost growth represents an important aspect of the overall water column injury.

4.4.5.4 Lack of Observed Dead Biota

Although the Trustees have concluded that exposure to DWH oil killed an unprecedented number of water column organisms in the northern Gulf of Mexico, it is important to understand that there is no reason to expect those effects to have manifested as a large, observable number of dead fish and invertebrates. A number of factors contribute to the low likelihood of visually observing the mortality quantified by the Trustees, including the following:

- Much of the injury to fish and invertebrates occurred in small, early-life stage organisms that would not have been seen. For context, these early-life stage organisms are generally smaller than the letters on this page.
- The spatial extent of injury was vastly greater than any practicably observable area and the exposure and resulting injuries were not uniform over the timespan and geographic extent of the spill.
- Dead fish would have been subject to rapid predation and decomposition. The likelihood of observing dead fish prior to predation or decomposition is extremely low given the spatial scales involved in the injury.
- The toxic effects of oil exposure to juvenile and adult fish are more likely to result in chronic injuries that will manifest differently by individual, rather than an acute effect that immediately kills a large school of fish.

This conclusion is also supported in the DWH Phase III expert report, which concludes that "oil pollution does not usually produce large fish kills, but affects populations through adverse effects on survivability, reproduction, prey, and habitats" (Boesch 2014).

4.4.6 Conclusions and Key Aspects of the Injury for Restoration Planning

The DWH incident resulted in a large, continuous release of oil into the northern Gulf of Mexico. The oil was released 1,500 meters deep over 87 days. It reached the surface and was transported hundreds of

kilometers by currents, winds, and waves. As a result, a highly diverse group of water column inhabitants were exposed to oil and injured.

As described in further detail below, the injury assessment showed the following:

- The Trustees estimated the spill resulted in a surface slick that covered a cumulative area of at least 112,100 square kilometers (43,300 square miles) for 113 days in 2010. The average daily extent of the oil footprint was 11,100 square kilometers (4,300 square miles).
- The estimated average daily volume of water under surface oil slicks exceeding a TPAH50 concentration of 0.5 µg/L was 57 billion cubic meters. As a comparison, this volume is approximately 40 times the average daily discharge of the Mississippi River at New Orleans.
- Water column resources injured by the spill include species from all levels in the northern Gulf of Mexico food web. Affected organisms include bacteria, estuarine-dependent species (e.g., red drum, shrimp, seatrout), and large predatory fish (e.g., bluefin tuna) that can migrate from the Gulf of Mexico into the Atlantic and as far as the Mediterranean Sea.
- The Trustees estimated that 2 to 5 trillion larval fish and 37 to 68 trillion invertebrates were killed in the surface waters as a result of floating oil and mixing of that oil into the upper water column. In the deep waters, the Trustees' assessment showed that exposure to DWH oil resulted in the death of between 86 million and 26 billion fish larvae and between 10 million and 7 billion planktonic invertebrates. Of these totals, 0.4 to 1 billion larval fish and 2 to 6 trillion invertebrates were killed in estuarine surface waters. The larval loss likely translated into millions to billions of fish that would have reached a year old had they not been killed by the spill. Larval fish that were killed but would not have survived to age 1 are also a significant loss; they are an energy source for other components of the ecosystem. The Trustees determined that additional injuries occurred, but these were not quantified. Examples include adverse effects to fish physiology (e.g., impaired reproduction and reduced growth) and adverse effects to reef fish communities (e.g., reductions in abundance and changes in community composition).
- The Trustees also quantified injury to *Sargassum,* a brown algae that is habitat for many marine animals. Up to 23 percent of the *Sargassum* in the northern Gulf of Mexico was lost due to direct exposure to DWH oil. The total loss of *Sargassum*, including foregone area from lost growth due to exposure to this oil, is 11,100 square kilometers.

The Trustees considered all of these aspects of the injury in restoration planning, and also considered the ecosystem effects and recovery information, described below.

4.4.6.1 Exposure

The Trustees used remote sensing imagery to quantify the area of surface oil observed floating on the ocean surface for the duration of the spill. Based on this imagery, the Trustees estimated the spill resulted in a surface slick that covered a cumulative area of at least 112,100 square kilometers (43,300 square miles) for 113 days in 2010. This surface oil slick occurred in an area of high biological

abundance, diversity, and productivity. Furthermore, the event occurred during a time of year (spring and summer) when seasonal productivity peaks in the northern Gulf of Mexico.

To estimate the spill's impacts on water column biota, the Trustees quantified the direct kill and production foregone of fish and invertebrates exposed to DWH oil both in the surface slick and in the subsurface mixed zone. The concentrations of PAHs in water below the surface slick were estimated using empirical chemistry data from water samples collected during the time oil was present on the water. The number of biota exposed to either the surface slick or lethal concentrations of PAHs was estimated from historical biological collections, NRDA field studies, and the literature. The number of biological organisms killed due to direct oil slick exposure or due to exposure to lethal concentrations of PAHs was estimated using data synthesized from NRDA-specific field studies, NRDA toxicity testing studies, and the published literature.

In addition to impacts from exposure to the surface slick and entrained oil from the surface slick, biota occupying the deeper water column (more than 20 meters beneath the surface) were also impacted by the cone of rising large oil droplets, dissolved components, and the deep water plume—a "cloud" of small oil droplets and dissolved contaminants. The NRDA sampling efforts in the deep ocean highlight the diversity and abundance of animals exposed to oil in the deep pelagic waters of the Gulf of Mexico. The Trustees used modeling and empirical data to quantify the direct kill of fish and invertebrates exposed to the rising cone of oil and to the deep water plume.

The Trustees estimated that 2 to 5 trillion larval fish and 37 to 68 trillion invertebrates were killed in the surface waters as a result of floating oil and mixing of that oil into the upper water column. Of these totals, 0.4 to 1 billion larval fish and 2 to 6 trillion invertebrates were killed in estuarine surface waters. In the deep waters, the Trustees' assessment showed that exposure to DWH oil resulted in the death of between 86 million and 26 billion fish larvae and between 10 million and 7 billion planktonic invertebrates, respectively. Depending on the species, survival from the larval size captured in survey nets to 1 year of age ranges from approximately one in a thousand to one in several million (French McCay et al. 2015d). This translates into a loss of millions to billions of fish that would have reached age 1. Additionally, the larval fish that were killed but would not have survived to age 1 are a significant loss; they are an energy source for other components of the ecosystem.

In addition to the lethal injuries quantified by the Trustees, injuries to fish physiology and reef fish communities were observed at a number of locations following the DWH oil spill. PAH concentrations measured in the Gulf of Mexico water column exceeded levels known to cause sublethal toxic effects to water column organisms. Sublethal toxic effects can reduce an organism's health, fitness, and ability to reproduce and survive. Following the DWH oil spill, field-collected data documented effects on fish physiology, including impaired reproduction and reduced growth, which can be associated with reduced survival and fecundity. Tissue lesions were also observed in red snapper and other bottom dwelling fish species on the continental shelf in the northern Gulf of Mexico (Murawski et al. 2014). Furthermore, injuries to shelf-reef communities were observed, including reductions in abundance and changes in community composition (Patterson III et al. 2015; Patterson III et al. 2014). Species-specific data for red snapper, a key recreational and commercial species and focus of intensive fisheries management effort, indicate that other injuries included growth reductions (Herdter 2014; Neese 2014; Patterson III 2015),

shifts in diet (Tarnecki 2014; Tarnecki & Patterson 2015), and increased prevalence of tissue lesions (Murawski et al. 2014). Exposure of DWH oil to these species was observed in carbon isotope ratios (Tarnecki & Patterson 2015) and was indicated by relatively high concentrations of PAHs in fish liver and bile (Murawski et al. 2014; Romero et al. 2014). Overall, although explicit quantification of these various injuries is not possible at this time, the Trustees concluded that fish and fish communities suffered physiologically and demographically important injuries in hard-bottom habitats along portions of the continental shelf.

The Trustees also quantified injury to *Sargassum,* a brown algae that creates essential habitat for invertebrates, fish, birds, and sea turtles. Trustees quantified the loss of *Sargassum* resulting from direct oiling and also the area of *Sargassum* foregone due to lost growth. Up to 23 percent of the *Sargassum* (1,749 square kilometers) in the northern Gulf of Mexico was lost due to direct exposure to DWH oil on the ocean surface. In addition, foregone *Sargassum* area from lost growth due to exposure to this oil was estimated to be as large as 9,400 square kilometers.

4.4.6.2 Ecosystem Effects

In addition to the quantification of lost individuals, the Trustees also considered potential ecosystem effects, including foodweb and ecological function impacts.

As discussed above, the Gulf of Mexico is a complex and interconnected ecosystem, composed of diverse habitats and species and important ecological processes. When natural resources are injured, cascading ecological effects can occur, including changes in trophic structure (such as altering predator-prey dynamics), community structure (such as altering the composition of organisms in an area), and ecological functions (such as altering the flow of nutrients).

Numerous studies have modeled the extensive food web of the Gulf of Mexico (e.g., Althauser 2003; Clough et al. 2015; de Mutsert et al. 2012; Masi et al. 2014; Tarnecki et al. 2015; Walters et al. 2008) with energy flowing from primary producers to large predators and trophic relationships connecting the nearshore and offshore as well as the surface and deep. Impacts to a specific resource could cause direct and indirect effects cascading throughout the food web (Fleeger et al. 2003; Peterson et al. 2003) (Fodrie et al. 2014; Tarnecki et al. 2015). For example, bottom-up trophic impacts could occur if an important food base, such as plankton or a forage fish, were impacted. Alternatively, impacts to a species higher on the food chain could reduce predation pressure, resulting in potential changes to the community structure and interspecific (between species) and intraspecific (within species) dynamics. Resources discussed in other sections, such as sea turtles, birds, and marine mammals, are also connected to the water column ecosystem through foodweb dynamics. Injuries to these resources could also cause potential trophic cascades to water column species.

Another potential concern includes impacts to ecological functions and processes. As discussed in Section 4.4.1, water column resources are important vectors of energy, both vertically and horizontally. Thus, impacts to a particular resource could alter the flow of organic carbon or nutrients through the water column, resulting in indirect effects to additional species and habitats.

As discussed in other sections of this document, nearshore and benthic environments are important habitats for many species found within the water column, serving as nursery grounds, foraging habitat,

and refuge from predators. During some part of their life cycles, many estuarine-dependent fish and crustaceans rely on nearshore habitats, such as marshes, submerged aquatic vegetation, and oyster reefs. As such, habitat losses, as described in Section 4.6 (Nearshore Marine Ecosystem), could cascade to impacts to water column resources.

4.4.6.3 Uncertainties

Given the magnitude and ongoing nature of the DWH oil spill, it was not possible to measure the locations of all species and water column oil concentrations over all affected areas. Thus, the Trustees inferred this information from available data and models. The approach to estimating mortality in the upper water column requires several assumptions that introduce uncertainty regarding the precision of the inferences and estimates that cannot be readily quantified. Among these are:

- The actual vertical distribution of the eggs and invertebrates in the upper water column is well-represented by the assumed distribution.
- The observed TPAH50 distribution is representative of the distribution of concentrations that were present in the areas of floating oil during the spill.
- The duration of egg or invertebrate exposure to TPAH50 is representative of exposure durations in the toxicity tests.
- The laboratory toxicity tests are applicable to the field conditions during the DWH spill.

Because this uncertainty cannot be known and quantified, the resulting effect on the upper and lower range of estimated mortalities cannot be determined, and the range may be greater than that expressed. However, the Trustees have relied on the best available information when making the above assumptions and believe the range of injury presented is reasonable and provides sufficient certainty to aid in restoration planning.

4.4.6.4 Recovery

The water column contains a diverse array of species, occupying different niches and interacting in a complex web of production, consumption, and decomposition. Water column resources injured by the spill include species from all levels in the food chain. Affected organisms include bacteria, estuarine-dependent species (e.g., red drum, shrimp, seatrout), and large predatory fish (e.g., bluefin tuna). With so many species, zones, and interconnections (see Section 4.4.1 for more detail), predicting natural recovery of the Gulf of Mexico water column ecosystem is necessarily also complex. While some organisms are expected to recover quickly, others may take many years to decades to fully recover. Small forage fish typically have high rates of turnover and thus might be expected to recover more quickly than longer lived fish like large tunas and some reef fish that can live for decades. However, the interactions among species and the feedbacks from one organism to another may alter these perceived recovery trajectories. Restoring key parts of the system that were injured will increase recovery rates for components of the ecosystem that were impacted and help to compensate for the losses that occurred over the recovery period.

4.4.6.5 Restoration Considerations

As described in Chapter 5, to restore for injuries to water column resources, the Trustees identified restoration that could benefit water column resources directly by reducing excess sources of mortality. The Trustees also identified restoration that can benefit water column resources indirectly, by restoring the habitats and biological relationships that these resources depend on, including restoring coastal and benthic habitats.

4.4.7 References

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