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Seafood and Beach Safety in the Aftermath of the Deepwater Horizon Oil Spill

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Partially buried oil at Pensacola Beach, Florida, showing oil deposited in intertidal (partially submerged) and supratidal (exposed) sands. Depending on the location of the oil burial, oil-degrading microbes are exposed to very different environmental settings, ranging from permanently submerged to permanently dry. The location of the buried oil also affects the oil's exposure to oxygen, nutrients, and heat and thus impacts the rates of microbial degradation. *Photo by Markus Huettel*

ABSTRACT. The 2010 explosion and sinking of the Deepwater Horizon oil platform in the Gulf of Mexico resulted in the largest oil spill the United States has ever endured. The oil spill raised many public health and environmental concerns, including those about the safety of Gulf seafood and public beaches. Analysis of seafood and coastal beaches in the aftermath of the oil spill indicated that public health risks from exposure to harmful crude oil residues returned to pre-spill levels soon after the oil spill had dissipated. However, the official seafood risk assessment elicited concerns about the inclusion of vulnerable populations, and gaps in toxicological knowledge and related risk information about many of the harmful components in crude oil. Residual crude oil may persist in water-saturated sediments and submerged oil mats that can act as sources for remobilization and future exposures. The response to the Deepwater Horizon event revealed a lack of adequate demographic and human health baseline data, benchmark environmental contaminant data, effective risk communication strategies, and integrated surveillance systems linking human and environmental health status and trends. The development of such knowledge would help improve responses and outcomes to future large-scale catastrophic events.

INTRODUCTION

The explosion and subsequent sinking of the Deepwater Horizon oil production platform (DWH) on April 20, 2010, resulted in the largest oil spill in US history. A Spill of National Significance was declared on April 29, as roughly 53,000 barrels of oil per day (1 barrel of oil ≈ 159 liters) flowed from the ruptured wellhead into the Gulf of Mexico (GoM). An estimated 4.9 million barrels of crude oil escaped before the damaged wellhead was sealed on July 15, 2010 (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011). The magnitude and duration of the DWH oil spill threatened the well-being of Gulf Coast communities, ecosystems, and services that the region provides to the nation. The largest industries in the region are energy, tourism, shipping, and fisheries. Petrochemical extraction and refining account for more than 50% of US domestic production, and approximately 50% of national shipping moves through Gulf ports, which number among the largest in the nation. Tourism accounts for about 20% of the regional economy, and Gulf fisheries produce about 16% of US domestic seafood landings (Shepard et al., 2013). The shoreline and coastal waters of the Gulf define cultures and economies, and provide habitat to more than 15,000 estuarine and marine species that are all inextricably linked to regional and national well-being (National Ocean Service, 2011).

The DWH oil spill impacted a 2,113 km long stretch of the Gulf Coast from Texas to Florida (Nixon et al., 2016). About 10 days after the DWH explosion, crude oil from surface slicks began washing onto GoM shorelines, contaminating sandy beaches stretching approximately 880 km from Louisiana to Florida. Tar balls appeared and stranded oil was buried as the beaches accreted sand over the following months, producing oiled sand layers up to 15 cm thick (OSAT, 2011; Michel et al., 2013; Wang and Roberts, 2013; McDaniel et al., 2015). The spread of surface and submerged oil led to the progressive closure of commercial, recreational, and subsistence fisheries where oil was observed and predicted to travel based on weather and currents. At the height of the oil spill in June 2010, coastal waters extending from Louisiana to the panhandle of Florida were closed to fishing, and 37% (229,271 km^2) of federal waters in the GoM Exclusive Economic Zone were closed. The reopening of fisheries began in the fall of 2010, and with the exception of heavily impacted areas of southern Louisiana, concluded in April 2011 (Ylitalo et al., 2012).

The contamination of GoM seafood and beaches with crude oil and dispersants used to mitigate the spill raised concerns about potential human health effects. Harmful crude oil hydrocarbons are a subset of the large number of chemical constituents in crude oil that are known to be toxic and may affect the lungs, liver, kidneys, and nervous system, or cause other systemic effects, although most of these effects are believed to occur only at high levels of exposure (Goldstein et al., 2011). A smaller subset of crude oil constituents is known to be genotoxic and carcinogenic, and may produce genetic damage and malignancies in humans at lower levels of exposure. The toxic and carcinogenic crude oil constituents are largely aromatic hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), a diverse class of organic chemicals found in crude oil and also formed by incomplete combustion of organic matter (e.g., wood, vegetation, fuel, food). They include benzene, which is present in crude oil at concentrations from 1% to 6% (Goldstein et al., 2011), and high molecular weight PAHs, which were present in approximately 3.9% of the crude oil from the DWH well (Allan et al., 2012). The high molecular weight PAHs present health concerns for seafood safety because of their persistence in the environment, potential for uptake in aquatic species, and toxic or carcinogenic effects (Harvey, 1991). PAHs are also health concerns for beach safety because tar balls formed from weathered crude oil that washes ashore and stranded oil mixed in sand are potential contact hazards and also fertile substrates for microbes, some of which are pathogenic (e.g., *Vibrio* species). These exposure scenarios, as well as the potential for heavy metals from crude oil to concentrate in seafood, are potential risks to public health. During and after the DWH oil spill, official public health responses (from the Food and Drug Administration, the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, and the Gulf states) and the adequacy of information about risks associated with crude oil was scrutinized to answer the questions: Are crude-oil-impacted Gulf of Mexico seafood and beaches safe, and how might risk information and response strategies be improved for the future?

ASSESSING SEAFOOD SAFETY

The official response to seafood safety concerns provoked by the DWH oil spill (US FDA, 2010) followed the basic approach used in response to the 1990 *Exxon Valdez* oil spill in Alaska (Bolger et al., 1996; Bolger and Carrington, 1999) and subsequent guidance (Yender et al., 2002)—accounting for differences in the physical and chemical natures of the crude oil spilled and the environmental conditions where the spill occurred. A panel of 13 PAHs and alkylated homologs that were prominent in DWH crude oil were targeted for analysis as indicators of human health risk posed by crude oil residues in seafood. Maximum allowable amounts (i.e., levels of public health concern) of PAHs in seafood were established that if exceeded and consumed daily for a period of five years would increase an upper-bound one in 100,000 risk level for cancer or adverse effects for non-cancer PAHs (US FDA, 2010; US EPA, 2000). These levels of concern were considered by officials to be safe or associated with negligible risk for the US population and, as appropriate, states would use state-specific data to make local and statewide determinations (US FDA, 2010). However, the risk level, estimated duration of exposure, and the use of national demographic values for body weight, consumption rate, and longevity were extensively scrutinized, as elaborated below.

The average time that DWH oil impacted areas were closed to fishing was 74 days (US FDA, 2014). As these areas cleared and remained free of surface oil, state and federal agencies began collecting and testing seafood samples for oil and dispersant contamination (July 2010 through August 2011). Results from testing about 10,000 samples indicated that Gulf seafood from reopened areas was safe for consumption. Individual toxic and carcinogenic PAHs were detected in many seafood samples at low concentrations at least two orders of magnitude below levels of public health concern. An indicator compound for Corexit dispersants, dioctyl sodium sulfosuccinate (DOSS), was detected in less than 1% of samples, also at low concentrations, and metals did not exceed background levels (Ylitalo et al., 2012). Independent sampling and testing during the same timeframe and afterward reported similar findings. In a study by Xia et al. (2012) of 25 individual PAHs in seafood, higher levels were measured in early sampling months as fisheries were being closed compared to later months as fisheries were reopened. In all samples, PAH levels did not exceed levels of public health concern, and were comparable to those measured in common processed foods purchased from local food outlets. Levels detected in oyster samples were comparable to 10-year historical data from the NOAA Mussel Watch program (https://products.coastalscience.noaa.gov/collections/ltmonitoring/nsandt).

A one-year study by Fitzgerald and Gohlke (2014) of PAHs, heavy metals, and dispersant residues in seven species of reef fish collected by commercial fishermen from March 2011 to April 2012 found two of 92 samples had detectable levels of seven PAHs measured. Metals were largely absent (cadmium, lead) or consistent with previously reported levels (mercury, arsenic), and DOSS was not detected. The study authors concluded that there was minimal risk to public health from seafood as a result of the disaster but cautioned that the most contaminated areas were not sampled during their study. In a probabilistic health risk assessment of 81 PAHs by Wilson et al. (2015), many of which were of unknown toxicological significance, and based on local shrimp consumption by Vietnamese-Americans in southeastern Louisiana, results indicated no acutely toxic or excess cancer risk associated with consumption of shrimp containing levels of PAHs found in their study, even among frequent shrimp consumers. And, a community-based study of more than 1,000 seafood samples collected by the public from 2011 to 2013 from the Florida Gulf Coast found that 74% of samples tested for PAHs were below quantifiable limits of detection, and the remaining samples contained PAHs at levels consistent with background and other cited studies (Kane, 2015). In related studies, Murawski et al. (2014) investigated reports of abnormal skin lesions and other pathologies in GoM fish following the DWH oil spill. Surveys of offshore fish populations were conducted in 2011 and 2012, and incidence of skin lesions were assessed in more than 7,000 specimens from 103 species collected from 150 sampling stations. Skin lesions were confirmed on primarily bottom-dwelling species in 2011, and decreased by 53% in 2012. Relatively high concentrations of PAH metabolites were detected in fish bile, while summed PAH levels measured in fish liver and muscle tissues were one to three orders of magnitude below levels of human health concern, as reported in previously mentioned studies.

Several other studies raised concerns that the official levels of public health concern established by public health agencies (Food and Drug Administration, National Oceanic and Atmospheric Administration, Environmental Protection Agency, and Gulf states) underestimated risks to vulnerable populations from seafood contaminants. In a study that proposed an alternative risk assessment, Rotkin-Ellman et al. (2012) cited the increased vulnerability of pregnant women and children, national demographic risk parameters, and insufficiently conservative estimates of exposure duration and acceptable risk level. The alternative levels of concern proposed by the authors were between two and four orders of magnitude below official levels. Applying these revised levels suggests that up to 53% of Gulf shrimp PAH levels exceeded the authors' revised levels of concern for pregnant women who are high-end seafood consumers. Similar concerns for vulnerable populations were expressed in the study of seafood consumption in a Vietnamese-American population in Louisiana (Wilson et al., 2015), and in a review of past and present responses to seafood safety issues following oil spills (Golke et al., 2011). These studies also recommend adoption of a more inclusive range of risk parameters, although in neither study were levels of concern exceeded nor were acute and excess cancer risks associated with consumption of the Gulf seafood, even when more conservative parameters were used to estimate risk.

BEACH POLLUTION BY DWH OIL

Surface oil impacting the Gulf shoreline was extensively modified by mixing with seawater, weathering, photooxidation, and biodegradation (Aeppli et al., 2012; Gros et al., 2014). It was deposited on Gulf beaches mostly as a thick, viscous emulsion containing up to 60% water (Figure 1a). Because of the heavy public use of beaches and concerns about potential impacts on human health and economy, manual and mechanical cleanup operations were conducted in 2010–2012 on approximately 660 km, or 73.3% of oiled beaches, to remove surface and buried oil (Hayworth and Clement, 2011; Michel et al., 2013). Where this cleanup was completed, oil remained in the beach environment mainly as surface residual balls (SRBs, typically <10 cm diameter) and submerged oil mats (SOMs) up to hundreds of meters long and 20 cm thick (Yin et al., 2015). Beginning in 2011, samples of buried oil sand layers contained 7% to 9% oil, SRBs 4% to 13%, and SOM 9% to 17% (OSAT, 2011). Because SRBs are relatively stable in the beach environment, presumably because of the properties of resins that provide cohesion to the oil and sand particles

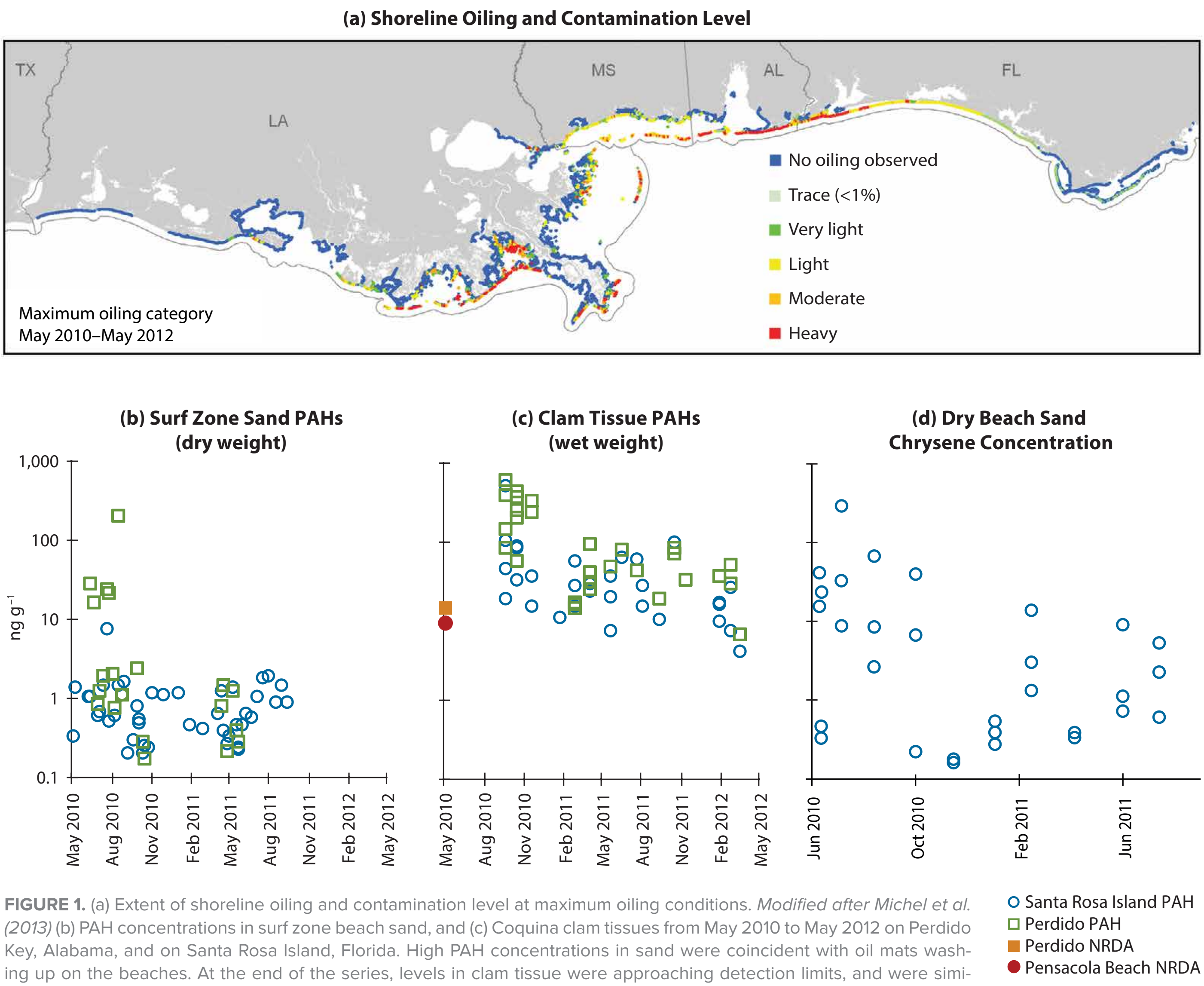

FIGURE 1. (a) Extent of shoreline oiling and contamination level at maximum oiling conditions. *Modified after Michel et al. (2013)* (b) PAH concentrations in surf zone beach sand, and (c) Coquina clam tissues from May 2010 to May 2012 on Perdido Key, Alabama, and on Santa Rosa Island, Florida. High PAH concentrations in sand were coincident with oil mats washing up on the beaches. At the end of the series, levels in clam tissue were approaching detection limits, and were similar to Coquina samples taken by Escambia County, Florida, officials prior to oil impacts for the Natural Resource Damage Assessment process on Perdido Key and Santa Rosa Island's Pensacola Beach. *Modified after Figure 5 in Snyder et al. (2014), reprinted with permission from Elsevier ©2014* (d) Chrysene concentrations in the dry beach at Pensacola Beach, Santa Rosa Island. *Modified after Hagan et al. (2013)*

(Lemelle et al., 2014; Warnock et al., 2015), they now are the primary form of oil observed on Gulf beaches. As a result of cleanup teams' removal of oiled sediments, the monthly amounts of SRBs collected decreased (Dalyander et al., 2014), although SOMs that formed in protected areas and near inlets still persist to the present day and act as sources for petroleum hydrocarbons that wash up on beaches as "new" SRBs after storm events (Hayworth et al., 2015). Nevertheless, SRBs and oil that was buried in sandy Gulf beaches are subject to continued weathering and biodegradation, and two years after the spill, heavy to moderately oiled shorelines had declined by 96% compared to the initial maximum oiling conditions (Michel et al., 2013). The relatively rapid decrease of oil contamination in Gulf beaches can be attributed to special circumstances that characterize the oil and the Gulf beach environment: the light, sweet Macondo crude oil (API gravity 35–40) released from the DWH well had a relatively low content (<1% wt/wt) of environmentally persistent resins and asphaltenes (McKenna et al., 2013); the warm temperatures of the Gulf environment supported high geochemical and biological oil degradation rates (Rowland et al., 2000); and the prevalence of bacteria capable of degrading oil (primarily Gammaproteobacteria, including Alcanivorax, Marinobacter, Pseudomonas, and Cinetobacter) resulted in a prompt response of the microbial community and biodegradation after oil deposition (Kostka et al., 2011; Bik et al., 2012; Lamendella et al., 2014; Rodriguez-R et al., 2015; Simister et al., 2015).

HEALTH RISKS ASSOCIATED WITH CONTAMINATED BEACH SAND AND WATER

To address health concerns associated with the stranded oil and SRBs, the Operational Science Advisory Team (OSAT, a team established to advise the federal on-scene coordinators about the residual oil on beaches and associated health risks) performed a human health risk assessment designed by the Florida Department of Health using 22 samples, including SRB, oiled sand, and SOM material collected from October 2010 to January 2011 from shorelines of Louisiana, Mississippi, Alabama, and Florida. The complete data set, including information on sampling locations is available from the ERMA® Deepwater Gulf Response website at https://gomex.erma.noaa.gov/erma.html. The assessment evaluates risks for two different exposure scenarios, a "Visitor" scenario that addresses the short-term exposure of a young child "visiting" a beach for 90 days over a 120-day period for one year, and an "Unrestricted" scenario that addresses long-term residential exposure (i.e., from childhood through adult daily exposure for 30 years). In both scenarios, exposure was assumed to result from skin contact with oiled sediment, ingestion of oiled sediment, and inhalation of vapors and dusts containing petroleum hydrocarbons. Twenty percent petroleum content of the samples was used for this analysis with the remaining portion being sand, sediment, or other nonpetroleum constituents, and exposures were adjusted to account for the fraction of the beach surface covered by the oil residues. In both the "Visitor" and "Unrestricted" exposure scenarios, the total risks from chemicals in each of the 22 samples analyzed were found to be below the most conservative Environmental Protection Agency (EPA) acceptable excess lifetime cancer risk level of one in 1,000,000. Correspondingly, the cumulative non-cancer risks for chemical concentrations detected in each of the 22 samples were less than the EPA-recommended criteria for noncarcinogens. These results indicated that short- and long-term exposures to the petroleum hydrocarbon concentrations occurring at the Gulf beaches would not cause unacceptable health risks; however, the number of samples used for this study was relatively small. OSAT supported its statement by the finding that oil samples collected at the end of 2010 and beginning of 2011 were 86%–98% depleted in total PAHs. In most locations, models predicted PAH concentrations in oil buried in the beach sand to decrease to 20% of the 2011 levels by 2016.

In contrast to the toxicological impacts of the oil hydrocarbons and chemical dispersants, relatively little attention has been paid to the potential health threat of metals in the DWH crude oil, which include nickel (~1.5 $\mu g\ g^{-1}$) and chromium (~9.5 $\mu g\ g^{-1}$). Like some PAHs, Ni and Cr can be genotoxic and carcinogenic. In SRBs collected from Gulf of Mexico beaches, Wise et al. (2014) measured Ni concentrations up to 8.5 $\mu g\ g^{-1}$, and Cr concentrations up to 4.8 $\mu g\ g^{-1}$. Liu et al. (2012) reported similar concentrations for these metals in DWH oil mousse. In seawater, for comparison, the respective concentrations of Ni and Cr were 0.00014 $\mu g\ g^{-1}$ and 0.00017 $\mu g\ g^{-1}$ or less. Although small concentrations of mutagenic chemicals can cause DNA damage, cancer caused by these metals typically is seen in people who were exposed over longer periods of time and to high concentrations of these metals (e.g., in nickel refineries or ferrochrome production facilities).

The health risks associated with stranded oil and SRBs on the sandy beaches may also include biological hazards. Tao et al. (2011) examined SRBs for aerobic bacteria counts and the presence of *Vibrio vulnificus*, a human pathogen common in Gulf Coast environments and capable of causing severe wound infections. Their results showed that *Vibrio vulnificus* numbers in SRBs were 10 times higher than in the surrounding sand and up to 100 times higher than in the seawater. Although the tenfold increase of *V. vulnificus* has to be seen relative to the natural high variability of sedimentary microbial populations, these results suggest that SRBs can act as reservoirs for bacteria, including human pathogens.

To reduce potentially harmful effects of the DWH oil deposited on Gulf beaches, 73% of oiled beaches, many of which are popular with beachgoers, were cleaned manually and with machinery (Michel et al., 2013). In contrast, the nearshore waters could not be cleaned, and the question arises as to whether oil contaminants in the seawater posed a health risk to swimmers. The carcinogenic and highly water-soluble benzene was retained in the deepwater column and therefore was nearly absent at depths shallower than 1,000 m. Likewise, the soluble low molecular weight 10- and 12-carbon PAHs (e.g., naphthalenes) that contributed about 64% to the DWH source oil PAH pool (Liu et al., 2012) are easily volatilized and degraded. A substantial fraction of these components dissolved, evaporated, or decomposed before reaching the coast. Larger PAHs on the other hand are hydrophobic, resistant to degradation, and reached the shore.

For the assessment of pollutant trends in coastal waters, where concentrations vary substantially on short time scales due to tides, winds, and shoreline currents, biological indicators are recognized as useful tools for contaminant bioavailability and for monitoring compounds that may be present below analytical detection limits. For example, the National Oceanic and Atmospheric Administration's (NOAA's) longstanding Mussel Watch program (http://celebrating200years.noaa.gov/datasets/mussel/welcome.html) uses filter-feeding bivalves that take up contaminants through water filtration and direct contact with contaminated water and sediment as indicators of bioavailable environmental pollutants (Figure 1b–d). In the foreshore swash zone of sandy Gulf beaches, Coquina clams are common small mollusks that filter the seawater washed by waves onto the beach and thus may also be good indicator species for monitoring oil contamination in the shallow water near Gulf beaches where people swim and possibly contact oil pollutants. Snyder et al. (2014) used the Coquina clams *Donax variabilis* and *Donax texasianus* from the surf zone of Florida Panhandle beaches to monitor PAH contamination to complement analysis of surf zone sand samples. The clams had higher levels of PAHs relative to surrounding sand, which allowed monitoring of PAH levels after sand PAH concentrations fell below detection limits. PAH levels decreased continuously in the surrounding sand and in the Coquina tissues (Figure 1b,c), reaching limits of detection within one and two years, respectively, after oil landed on Florida Panhandle beaches. The surf sand PAH concentrations reached highest values during and immediately after oil came ashore, but with less than 1 $\mu g\ g^{-1}$ total PAH concentration (Snyder et al., 2014), never exceeded Florida Department of Environmental Protection sediment contamination guidelines (levels of concern in coastal sediments: 0.8 $\mu g\ g^{-1}$ for benzo[a]pyrene and 17 $\mu g\ g^{-1}$ for total PAHs [MacDonald, 1994]). By fall of 2010, sand PAH concentrations had dropped below reporting limits. The decline of PAHs reported by Snyder et al. (2014) for the intertidal beaches was also found by Hagan et al. (2013) in supratidal beaches. The latter study, conducted at Pensacola Beach, revealed decreasing chrysene (a PAH) concentrations in the dry beach sand of Santa Rosa Island, reaching background levels one year after the accident (Figure 1d). This is critical information for health risk assessments because people may be exposed to the dry beach sand more frequently than to the intertidal beach sand, and because high molecular weight PAHs such as chrysene and benzo[a]pyrene are less biodegradable and can have higher toxicity than the low molecular weight PAHs (Hadibarata et al., 2009).

EVALUATING SEAFOOD AND BEACH SAFETY

Although most of these results indicated that DWH crude oil contamination of Gulf seafood and beaches returned to background levels soon after the oil spill had dissipated and the beaches and seafood were considered safe, PAHs may persist to the present day in water-saturated sediments and submerged oil mats that may be sources for remobilized PAH exposures (Yin et al., 2015) after the passage of winter cold fronts with strong northerly winds, tropical storms, and hurricanes (e.g., Tropical Storm Lee, September 2011 and Hurricane Isaac, August 2012). The results of the Snyder (2014) study suggest that Coquina clams may be suitable biological sentinels for monitoring episodic remobilization events that would be difficult to capture by standard water monitoring procedures. Monitoring of known harmful crude oil constituents in the environment and seafood may provide indications of persistence and potential health threats associated with PAHs in remobilized crude oil. Decomposition products, however, may be toxic as well; for example, intermediates of PAH degradation, particularly dihydrodiols, may

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be more toxic than their parent compounds. Synergistic effects, including known interactive and cumulative effects of multiple harmful substances occurring in the same environment, may also produce health risks (Turner et al., 2014). Low concentrations of a subset of known harmful crude oil constituents, such as the EPA priority PAHs typically used for environmental assessments, may not be sufficient to assess the states of seafood and Gulf sandy beaches. The official seafood health risk assessment raised concerns about the inclusion of vulnerable populations (Golke et al., 2011; Rotkin-Ellman et al., 2012; Wilson et al., 2014) and about critical gaps in toxicological data and related risk information on the majority of PAHs in crude oil (Wickliffe et al., 2014). Furthermore, the list of 16 EPA priority PAHs (Keith, 2015) widely used for environmental and health risk assessments in the last 40 years may be too limited to describe toxic potential because it may exclude some larger PAHs, alkylated PAHs, and compounds containing heteroatoms (Andersson and Achten, 2015).

The complete recovery of the Gulf ecosystem from the DWH oil spill may take decades. To determine the long-term risks associated with the DWH oil, the National Institute of Environmental Health Sciences in February 2011 launched the largest, most comprehensive study of long-term health effects from an oil spill, the Gulf Long-term Follow-up (GuLF) Study (https://gulfstudy.nih.gov). This study is anticipated to run at least a decade, and may inform future assessments of public health impacts from exposures to crude oil constituents and dispersants.

Since the introduction of the testing with 16 EPA priority PAHs in 1976, advances in analytical methods and knowledge of PAH toxicity, metabolism, and decomposition pathways have significantly improved our understanding of these substances and their toxic effects. However, only a fraction of this knowledge has been applied to environmental and public health monitoring. The DWH oil spill made clear that more research is required to address environmental contaminant toxicology, pathways of metabolism, and decomposition and methods to detect and characterize contaminants in diverse matrices. Particularly in the case of crude oil spills, alkylated PAHs, and higher molecular weight and substituted PAHs may be a good start (Andersson and Achten, 2015). Successful responses to and evaluations of public health and environmental effects from catastrophic events are also dependent on the availability of baseline monitoring data. The DWH accident revealed the lack of adequate demographic and human health baseline data, benchmark environmental contaminant data, effective risk communication strategies, and accessible integrated surveillance systems linking human and environmental health status and trends. Such developments would help improve responses and outcomes to future large-scale catastrophic events.

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