Marine Pollution Bulletin 126 (2018) 488–500

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Degradation of Deepwater Horizon oil buried in a Florida beach influenced by tidal pumping

Markus Huettel[a,*], Will A. Overholt[b], Joel E. Kostka[b], Christopher Hagan[a,1], John Kaba[a,2], Wm. Brian Wells[a], Stacia Dudley[a,3]

[a] Florida State University, Department of Earth, Ocean and Atmospheric Science, 117 N Woodward Ave., Tallahassee, FL 32306, United States
[b] Georgia Institute of Technology, Schools of Biology and Earth & Atmospheric Sciences, 310 Ferst Drive, Atlanta, GA 30332-0230, United States

ARTICLE INFO

Keywords:
Deepwater Horizon
Oil spill
Beach contamination
Microbial degradation
Pensacola Beach
Tidal pumping

ABSTRACT

After Deepwater Horizon oil reached the Florida coast, oil was buried in Pensacola Beach (PB) sands to ~70 cm depth, resulting in Total Petroleum Hydrocarbon (TPH) concentrations up to ~2 kg per meter of beach. This study followed the decomposition of the buried oil and the factors influencing its degradation. The abundance of bacteria in oiled sand increased by 2 orders of magnitude within one week after oil burial, while diversity decreased by ~50%. Half-lives of aliphatic and aromatic hydrocarbons reached 25 and 22 days, respectively. Aerobic microbial oil decomposition, promoted by tidal pumping, and human cleaning activities effectively removed oil from the beach. After one year, concentrations of GC-amenable hydrocarbons at PB were similar to those in the uncontaminated reference beach at St. George Island/FL, and microbial populations that disappeared after the oil contamination had reestablished. Yet, oxihydrocarbons can be found at PB to the present day.

1. Introduction

The oil slick produced by the 2010 Deepwater Horizon (DWH) accident in the Gulf of Mexico covered an average area of 11,200 km^2 (Garcia-Pineda et al., 2013; MacDonald et al., 2015) that moved mainly in a northeast direction toward the US-shoreline (Mezic et al., 2010). Exposure to O_2, seawater and light weathered the floating oil and decreased its volatile components (C9-C16 n-alkanes and BTEX/C3-benzenes) (Liu et al., 2012). Model estimates suggest that 22,000 t of this weathered oil reached the coast (Boufadel et al., 2014).

By 11th of May 2010, oil began washing onto the shores of Louisiana, and later the coasts of Mississippi, Alabama, Florida and Texas, eventually polluting 965 km of sandy beaches (Hayworth et al., 2015; Michel et al., 2013; Mulabagal et al., 2013; Nixon et al., 2016; OSAT, 2011; Yin et al., 2015). Immediate initiation of massive clean up activities removed a large fraction of the surface oil, but sand moved by wind, waves, and human activities buried oil sheets and oiled sands (Wang and Roberts, 2013). Shielded from photooxidation and mechanical dispersion (King et al., 2014; Prince et al., 2003), buried oil can persist in beach sediments for years to decades as found after the Prestige and Exxon oil spills (Bernabeu et al., 2009; Boufadel et al., 2010).

The oil degradation within the sediment is mainly mediated by bacteria and fungi (Bik et al., 2012; Leahy and Colwell, 1990; Simister et al., 2015). Kostka et al. (2011) identified 24 oil-degrading bacterial strains in DWH-oiled Gulf of Mexico beach sands, and the increase of the relative abundance and expression of functional genes involved in oil decomposition confirmed the microbial degradation process in the sand (Kappell et al., 2014; Kimes et al., 2014; King et al., 2015; Lamendella et al., 2014; Rodriguez-R et al., 2015). The microbial degradation rates are mainly controlled by the quality of the oil, temperature, availability of nutrients, and access to O_2 (Hazen et al., 2016; Head et al., 2006; Joye et al., 2016; Prince, 2010.). Oil degradation increases with temperature up to ~37 °C; at higher temperatures, rates become limited due to protein denaturation and membrane toxicity of the hydrocarbons (Rowland et al., 2000; Sikkema et al., 1995; Vyas and Dave, 2007). Because crude oil contains low concentrations of major nutrients (nitrogen, phosphorus), application of fertilizer and the

* Corresponding author.
E-mail addresses: mhuettel@fsu.edu (M. Huettel), waoverholt@gmail.com (W.A. Overholt), joel.kostka@biology.gatech.edu (J.E. Kostka), haganc@goldmail.etsu.edu (C. Hagan), johnrkaba@gmail.com (J. Kaba), wbw08@my.fsu.edu (W.B. Wells), sdudl001@ucr.edu (S. Dudley).
[1] Present address: East Tennessee State University, Gatton College of Pharmacy, Johnson City, TN, 37614-0661, United States.
[2] Present address: Florida Department of Environmental Protection, 2600 Blair Stone Road, Tallahassee FL 32309, United States.
[3] Present address: University of California, Riverside, Environmental Toxicology, Riverside, CA, 92521, United States.

http://dx.doi.org/10.1016/j.marpolbul.2017.10.061
Received 27 December 2016; Received in revised form 25 September 2017; Accepted 21 October 2017

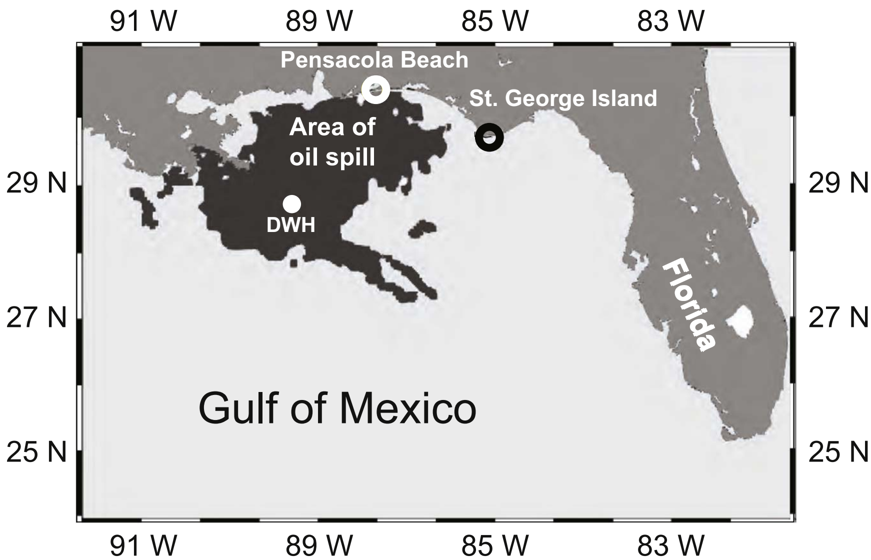

Fig. 1. Map of the study area. White circle: location of the study site on Santa Rosa Island at the public beach of Pensacola Beach/Florida. Black circle: Reference site at St. George Island. White solid dot: Location of the Deepwater Horizon accident. Dark grey area shows the area reached by the surface oil slick as detected by satellite pictures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
(Source: modified after Garcia-Pineda et al., 2013).

presence of natural organic matter can accelerate microbial oil decomposition (Atlas and Hazen, 2011; Horel et al., 2014; Mortazavi et al., 2013). Oil degradation typically progresses at much faster rates in aerobic environments (Leahy and Colwell, 1990), and can be negligible under anoxic conditions (Prince, 2010.; Reddy et al., 2002). One major difference between water column and sedimentary oil degradation is that the growth of heterotrophic microorganisms in oiled sediments often results in the local depletion of O_2 (Fernandez-Alvarez et al., 2006), which leads to the preservation of buried hydrocarbons. For example, hydrocarbons contained in submerged DWH oil mats (SOM) buried along Gulf shores showed little evidence of biodegradation in contrast to the oil in surficial residual balls (SRB) that accumulated on exposed beach surfaces (Elango et al., 2014; McDaniel et al., 2015). In sandy beaches, O_2 is supplied to buried oil by diffusion and airflow through sediment pores, or by O_2-rich groundwater (Geng et al., 2015; Heiss et al., 2014; Turner and Nielsen, 1997). In the lower beach, tidal groundwater water level oscillations within the sand (tidal pumping) can affect O_2 concentrations by enhancing water and air circulation (Charbonnier et al., 2013; Li et al., 2005). Nonetheless, oil buried in sandy shores can be a source for harmful polycyclic aromatic hydrocarbons (PAHs) for decades as found after the Gulf war (Bejarano and Michel, 2010).

The subsurface contamination of Gulf beaches thus raised concerns regarding the potential impact of toxic oil components on environmental and human health (Dickey and Huettel, 2016). To address problems that could arise from buried oil, BP conducted “Operation Deep Clean” designed to mechanically extract larger oil-sand aggregates from Louisiana, Alabama and Florida beaches (Hayworth and Clement, 2011). ODC removed the contaminated beach sand with a specifically designed oil cleaning/sifting machine dubbed the “Sand Shark” that removed sand to a depth of ~45 cm and separated particles > 2 mm from the sand. Some deeper oil was removed by excavators that put the contaminated sand onto a separate sifter. The sifted sand was re-deposited onto the beaches. Despite these activities and substantial research efforts (see review by Beyer et al., 2016), it was not possible to assign categorical oiling descriptors to the numerous subsurface oiling observations (Michel et al., 2013; Nixon et al., 2016) and the processes controlling buried oil decomposition and decay rates remained largely unquantified.

We therefore initiated a project that studied the degradation of the buried oil and the mechanisms controlling its decomposition. Research was guided by the working hypotheses that the burial of the oil triggered blooms of aerobic microbial communities in the sand that degraded oil particles and oil adhering to sand. We further hypothesized that these blooms of bacteria could rapidly degrade petroleum hydrocarbons because tidal pumping kept the oiled sediment layer aerobic. To investigate these hypotheses, the project addressed the following main goals:

1. Quantify the concentration changes of aliphatic and aromatic oil components buried in the beach over time.
2. Assess the abundance, composition and succession in the sedimentary microbial communities, and
3. Determine the transport of O_2 and CO_2 across the surface of the beach, and the gradients of O_2, temperature and moisture within the beach.

These research goals were addressed through a one-year time series study at Pensacola Beach/Florida, in-situ flux chamber experiments, and laboratory tide simulator experiments.

2. Methods

2.1. Study sites

The field work was conducted from June 2010 to July 2011 at Pensacola Beach (PB), Florida (30°19′32.08″N, 87°10′30.55″W) (Fig. 1), where the municipal beach was heavily polluted by oil after the DWH accident (Michel et al., 2013). The sediments at PB are composed of well-sorted medium quartz sand with low carbon and nitrogen content (Table 1). The tides at PB are diurnal, with a range of 12 cm (neap tide) to 61 cm (spring tide). The reference site was a sandy beach at St. George Island (SGI, 29°41′8.63″N, 84°47′17.10″W), which is situated approximately 350 km east of PB and was not impacted by the DWH spill. Except a slightly lower median grain size, the sands at SGI were similar in their characteristics to those at PB (Table 1).

2.2. Assessment of the distribution of oil, microbes and key environmental parameters in the beach

Measurements and sampling at the study site took place in 2010 on June 30, July 25 and 30, September 1, October 20, and December 2, and in 2011 on January 19, March 2, April 21, and June 16. To assess the distribution of the oil, microbes, O_2, temperature and moisture in the beach, we excavated trenches perpendicular to the water line (approximately 10–13 m long, 1–1.4 m deep and 1 m wide), reaching from the beach face to the landward edge of the beach oil contamination. Immediately after the excavation of one trench segment, O_2 optode