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Response of salt marshes to oiling from the *Deepwater Horizon* spill: Implications for plant growth, soil surface-erosion, and shoreline stability

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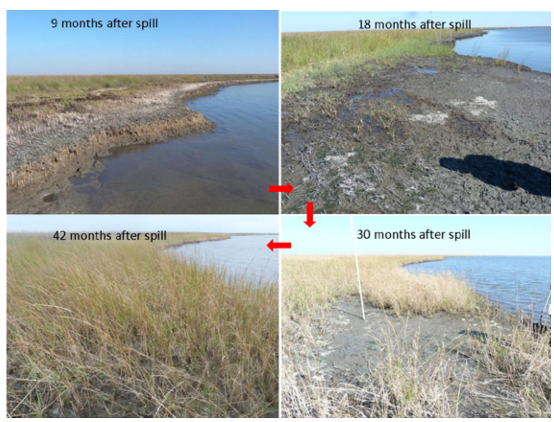
HIGHLIGHTS

- The *Deepwater Horizon* oil spill was the largest marine oil spill in U.S. history.
- The impact to and recovery of oiled salt marsh vegetation and soils were assessed.
- Moderately oiled marshes were initially affected but recovered within 2.5 years.
- Heavily oiled marshes were highly impacted and full recovery did not occur.
- Heavy oiling reduced soil shear strength and accelerated marsh surface erosion.

GRAPHICAL ABSTRACT



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ABSTRACT

We investigated the initial impacts and post spill recovery of salt marshes over a 3.5-year period along northern Barataria Bay, LA, USA exposed to varying degrees of *Deepwater Horizon* oiling to determine the effects on shoreline-stabilizing vegetation and soil processes. In moderately oiled marshes, surface soil total petroleum hydrocarbon concentrations were ~70 mg g^{-1} nine months after the spill. Though initial impacts of moderate oiling were evident, *Spartina alterniflora* and *Juncus roemerianus* aboveground biomass and total live belowground biomass were equivalent to reference marshes within 24–30 months post spill. In contrast, heavily oiled marsh plants did not fully recover from oiling with surface soil total petroleum hydrocarbon concentrations that exceeded 500 mg g^{-1} nine months after oiling. Initially, heavy oiling resulted in near complete plant mortality, and subsequent recovery of live aboveground biomass was only 50% of reference marshes 42 months after the spill. Heavy oiling also changed the vegetation structure of shoreline marshes from a mixed *Spartina–Juncus* community to predominantly *Spartina*; live *Spartina* aboveground biomass recovered within 2–3 years, however, *Juncus* showed no recovery. In addition, live belowground biomass (0–12 cm) in heavily oiled marshes was reduced by 76% three and a half years after the spill. Detrimental effects of heavy oiling on marsh plants also

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corresponded with significantly lower soil shear strength, lower sedimentation rates, and higher vertical soil-surface erosion rates, thus potentially affecting shoreline salt marsh stability.

1. Introduction

The *Deepwater Horizon* (*DWH*) oil platform explosion on April 20, 2010 and subsequent release of a judicially-determined 3.19 million barrels (506×10^6 L) of crude oil into the Gulf of Mexico (GOM) over the next 87 days was the largest documented marine oil discharge in the United States (Mendelssohn et al., 2012; Malakoff, 2015), having an unprecedented potential for damage. Spanning from Louisiana to Florida, *DWH* oiling was documented along approximately 1800 km of GOM coastal shoreline, including about 900 km of beach and 800 km of marsh (Michel et al., 2013). Without question, the Mississippi River Delta (MRD) – the nation's largest and most productive estuary – bore the brunt of the impact. Approximately 95% of the total marsh oiling occurred in coastal Louisiana, including 135 km of heavily oiled *Spartina alterniflora*- and *Juncus roemerianus*-dominated salt marshes located primarily in northern Barataria Bay, Louisiana, USA (Michel et al., 2013; Zengel et al., 2014).

The MRD wetland ecosystem is a nationally important estuary that contains approximately 40% of the coastal wetlands within the conterminous United States, and hosts a suite of ecologically and economically important services, including flood and storm protection, fisheries support, sediment and carbon sequestration, water quality improvement, and many others (Costanza et al., 1997; Costanza et al., 2008; Engle, 2011). However, MRD wetlands experience among the nation's highest land loss rates (43 ± 8 km^2 yr^{-1} from 1985 to 2010; Couvillion et al., 2011). Approximately 60% of this wetland loss occurs in the Barataria and Terrebonne basins (ROR, 2015), which includes the most heavily *DWH*-oiled coastal wetlands (Michel et al., 2013). Although wetland loss results from multiple causes (Day et al., 2007), further degradation and loss of this resource due to oiling impacts is of utmost concern to the northern Gulf of Mexico, as well as to the nation.

In general, the severity of oil impacts on coastal wetlands are complex and depend on a variety of factors such as oil type, degree of oil weathering and toxicity, oil-spill volume, mode and extent of contact with the vegetation, shoreline orientation, species-specific oil tolerance, oiling frequency, season (growing vs. dormant), climate, and especially oil penetration into the soil, among others (Alexander and Webb, 1987; Baca et al., 1987; Mendelssohn et al., 1990; Hoff et al., 1993; Lin and Mendelssohn, 1996, 1998, 2008, 2009; Hester and Mendelssohn, 2000; Pezeshki et al., 2000; Lin et al., 2002; DeLaune et al., 2003; Culbertson et al., 2008; Mendelssohn et al., 2012; Michel and Rutherford, 2014, Zengel et al. 2016a). Acute short-term impacts resulting from the *DWH* spill were evident in many shoreline marshes, particularly in the most heavily oiled areas adjacent to Bay Jimmy in northern Barataria Bay, Louisiana, where complete mortality of aboveground vegetation occurred within months after oiling (Silliman et al., 2012; Lin and Mendelssohn, 2012; Zengel et al., 2015). Although some vegetative recovery, indicating resilience, has been reported (Lin and Mendelssohn, 2012; Silliman et al., 2012), areas exhibiting little to no recovery also exist, which suggests lingering, longer-term impacts (Lin and Mendelssohn, 2012; Zengel et al., 2015). Of particular concern are reports of heavy oil exposure weakening soils, creating undercuts along the marsh edge, and thereby accelerating shoreline erosion after vegetation die-off (Silliman et al., 2012) and during recovery (McClenachan et al., 2013; Zengel et al., 2015). Although marsh undercutting due to wave energy and subsequent marsh slumping along shorelines is a normal erosional process in the MRD (DeLaune et al., 1994; Nyman et al., 1994; Watzke, 2004), oil exposure could accelerate this process. Post-spill impacts to aboveground vegetation have been primarily implicated as a driver of marsh loss (Silliman et al., 2012), however, other factors, such as viable plant belowground structures, could also be controlling shoreline erosion by reducing soil shear strength (Tengbeh, 1993; Baets et al., 2006; Sasser et al., 2013), and thus, affecting shoreline saltmarsh stability and sustainability.

Here, we present results from a 3.5-year investigation of *DWH* oiling impacts on salt marsh plant structure, above- and belowground biomass, and soil stability. Given the unique characteristics of the *DWH* oil spill, the long-term ecological impacts and pace of ecosystem recovery could differ from previous oil spills, providing invaluable predictive information for understanding coastal wetland sustainability after large-scale disturbances, including future oil spills. Because marsh plants act as foundation species, their recovery from disturbance may be necessary before the full range of biota recovers and marsh ecosystem services are fully restored (Fleeger et al., 2015, Zengel et al. 2016b). Our objectives were to (1) quantify above- and below-ground impacts resulting from both heavy and moderate *DWH* shoreline marsh oiling, (2) determine selected aspects of structural and functional recovery of impacted salt marshes, and (3) identify factors that may control the long-term sustainability of oiled shoreline marshes in the northern GOM.

2. Materials and methods

2.1. Site description and experimental design

On January 6, 2011, we established 21 shoreline (within 3 m of bay waters) sampling stations in and around Bay Jimmy located in northern Barataria Bay, Louisiana, USA (coordinates N 29.44060°–29.47459°, W 89.88492°–89.94647°), including shoreline marshes most severely impacted by the *DWH* oil spill (Fig. 1). Sampling stations were randomly selected within three distinct oiling categories: no apparent oiling (i.e., reference), moderate oiling, or heavy oiling ($n = 7$ per category). Oiling categories were determined from (1) Shoreline Cleanup Assessment Technique (SCAT) data, (2) our field observations of the severity of oil coverage on wetland plant shoots and marsh soil, and (3) station-specific soil-surface (0–2 cm) total petroleum hydrocarbon (TPH) determinations (see below for analytical methods). Heavily oiled marshes (HVOM) had a thick coating of viscous, emulsified oil that completely covered plant shoots, most of which were laid down horizontally, and coated the soil surface; the average TPH concentration was 511 ± 231 mg g^{-1} dry soil in January 2011. Moderately oiled marshes (MDOM) generally had partial oil coverage on the lower portion of plant shoots, most of which were able to maintain a vertical position, in combination with intermediate soil-oil concentrations in the soil; the average TPH concentration was 70 ± 38 mg g^{-1} dry soil in January 2011. Reference marshes (RFM) had no visual oil either on shoots or soils (the average TPH concentration was 0.6 ± 0.1 mg g^{-1} dry soil in January 2011). Reference marsh TPH was assumed to be primarily biogenic, and was subtracted from the soil TPH concentrations at all oiled stations, resulting in a more accurate estimate of petrogenic TPH.

The heavily oiled sites had not received cleanup as of January 2011 as evidenced by the presence of rooted plants shoots, dead standing vegetation and stubble, and intact soil surfaces with oil still present. After marking and recording the GPS position of our sampling locations, this information was submitted to the Unified Command by the *DWH* SCAT program to request that these sites not be cleaned (40 m of linear shoreline for each sampling station) because of scientific research (Zengel and Michel, 2013). Sampling occurred every 5–6 months over a 33-month period between January 2011 and November 2013, corresponding with 9 to 42 months after the *DWH* oil spill. During this