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

Qianxin Lin a,⁎, Irving A. Mendelssohn a, Sean A. Graham a,d, Aixin Hou b, John W. Fleeger c, Donald R. Deis e

a Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA
b Department of Environmental Sciences, Louisiana State University, Baton Rouge, LA 70803, USA
c Department of Biological Sciences, Louisiana State University, Baton Rouge, LA 70803, USA
d Department of Biological Sciences, Nicholls State University, Thibodaux, LA 70310, USA
e Atkins, Jacksonville, Fl. 32256, USA.

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

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
1. Introduction

The Deepwater Horizon (DWH) oil platform explosion on April 20, 2010 and subsequent release of a judicially-determined 3.19 million barrels ($506 \times 10^6$ $L$) 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 roemeri- nus-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 contiguous 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 ($43 \pm 8$ $km^2$ $yr^{-1}$ from 1985 to 2010; Couvillon et al., 2011). Approximately 60% of this wetland loss occurs in the Barataria and Terrebonne basins (GOR, 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; Hoffman 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; Silliman 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 89.84892°–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 $511 \pm 231$ 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 $70 \pm 38$ 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 $0.6 \pm 0.1$ 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 oil 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

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time, no obvious cleanup activities had occurred at our sampling locations.

2.2. Petroleum hydrocarbons

We determined residual total petroleum hydrocarbon (TPH) concentrations in the surface soil (0–2 cm) by collecting composite samples from 5 locations at each station during each sampling event. All samples were immediately placed in glass sampling jars stored on ice and transported to the laboratory in coolers for subsequent analysis. Soil TPH was extracted using dichloromethane and determined gravimetrically to the nearest 0.0001 g (Lin and Mendelssohn, 1996, 2012). The average of the DCM extractable biogenic hydrocarbons (primarily plant-derived natural sources), determined from samples collected in reference marshes, was subtracted from TPH determinations to yield petrogenic TPH, although biogenic TPH was <0.5% of TPH levels in the oiled marshes. Soil TPH concentration was expressed as mg g⁻¹ dry soil.

Polycyclic aromatic hydrocarbons (PAHs) and alkanes were determined by gas chromatography/mass spectrometry (GC/MS). Macondo MC252 source oil and composited heavily oiled marsh soils collected nine months after the spill were extracted with dichloromethane (DCM). Oil chemical components were analyzed by GC/MS in the selective ion monitoring mode by the Department of Environmental Sciences/Response and Chemical Assessment Team directed by Dr. Ed Overton at Louisiana State University. The GC/MS instrumentation used was a Hewlett-Packard 5980 GC configured with a DB-5 high resolution capillary column (0.25 mm i.d., 30 m, 0.25 μm film, J&W Scientific) directly interfaced to a Hewlett-Packard 5971 MS detector system. The targeted constituents, quantitation ions, and chromatographic conditions can be found in Lin and Mendelssohn (2009).

2.3. Aboveground biomass and stem density

We determined plant aboveground biomass and stem density at each station during each sampling within a haphazardly located 0.25 m² quadrat. All plants rooted within the quadrat were then clipped to the ground surface and separated into live and dead components by species. Stem density was determined by counting the number of intact living stems for each dominant plant species. All aboveground biomass was then dried to a constant mass at 60 °C and weighed.

2.4. Belowground biomass

We determined belowground biomass by extracting a 7.62-cm diameter by 36-cm long soil core from each station during each sampling. Upon transfer to the laboratory, cores were sectioned into 6 cm segments and washed over a 2-mm mesh sieve to remove sediment and particulate organic matter. The material from each segment was then separated as live and dead roots and rhizomes, dried to a constant mass at 60 °C, and weighed.

Separately, we determined rates of belowground biomass accumulation using the in-growth bag technique. At each sampling station, two nylon mesh bags (5-cm diameter by 30-cm long) filled with peat were buried in the marsh soil in October 2011 (1.5 years after the oil spill) and extracted after deployment for 6 and 12 months. Upon retrieval, ingrowth bags were washed over a 2-mm mesh sieve to remove the peat packing material. The remaining ingrown roots and rhizomes were then dried to a constant mass at 60 °C and weighed.

2.5. Soil shear strength

We determined soil shear strength using a 3.3-cm diameter by 5-cm long shear vane attached to a direct reading torque gauge (Geotechnics Ltd., Auckland, NZ). Soil shear strength was measured from the soil surface to a depth of 36 cm in 6-cm intervals at two locations within each station during all samplings except the January 2011 sampling. The procedure consisted of inserting the shear vane into the soil, twisting the vane until soil failure, pushing the vane into the soil an additional 6 cm, and repeating the measurement.

2.6. Soil accretion and erosion

We determined soil accretion as the vertical accumulation of mineral sediment and organic matter above a feldspar marker horizon laid down in a 0.25 m × 0.25 m plot at each sampling station on November 3, 2011. Two 2.5-cm diameter soil cores that penetrated the feldspar layer were then extracted 18 months after establishment. Upon
extraction, the depth of material deposited over the feldspar was measured to the nearest mm at two locations around each core and averaged (Cahoon and Turner, 1989). If no feldspar was visible (i.e., erosion occurred), we determined soil surface change relative to a PVC pole marked with the initial soil surface at the time of feldspar plot establishment.

2.7. Statistical analysis

All statistical analyses were conducted using SAS 9.3 and JMP 12 PRO (SAS Institute, Cary, NC). We used two-way mixed-model ANOVA (PROC Mixed) to identify the effects of oiling intensity, sampling period, and their interaction on measured variables. Prior to analysis, residuals were checked for normality and homogeneity of variance using normal quantile plots and residual plots, respectively. Where residuals were found to be normally-distributed or residual variances were not homogeneouse, we transformed the data to improve them: TPH, live aboveground biomass, and live stem density were square-root transformed, soil shear strength and live belowground biomass were log-transformed, and soil accretion was reciprocal transformed. Post-ANOVA, least squares means (LSMEANS) were used to evaluate differences among ANOVA main effects and individual treatment-level combinations. Significant differences between LSMEANS were determined by Fisher’s Protected Least Significant Difference test at a probability of p < 0.05, unless otherwise stated. We considered recovery of a response-variable to have occurred when that variable no longer significantly differed between reference and oiled marshes. The relationship between soil shear strength and live belowground biomass was quantified with linear regression analysis.

The data are archived with the Gulf of Mexico Research Initiative Information and Data Cooperative (http://griidc.gomri.org; Y1.x088.000:0006; Y1.x155.000:0001; Y1.x089.000:0002; Y1.x089.000:0003; R2.x211.000:0007).

3. Results

3.1. Concentrations of total petroleum hydrocarbon (TPH), PAHs and alkanes

Surface soil TPH concentrations were significantly higher in the HVOM (192.2 mg g\(^{-1}\) ± 40.3, n = 49) compared to both the MDOM (p < 0.005, 18.98 mg g\(^{-1}\) ± 6.46, n = 49) and reference (p = 0.0001, 0.36 mg g\(^{-1}\) ± 0.04, n = 49) marshes. The MDOM also had significantly (p < 0.0005) elevated soil TPH concentrations compared to reference marshes. A significant (p < 0.05) oil category by sampling time interaction further showed that soil TPH concentrations in the HVOM and MDOM relative to reference marshes varied over time (Fig. 2): soil TPH in the MDOM was higher than the RF only during the first 36 months after the spill, while the HVOM soil TPH remained consistently higher than both the RF and MDOM throughout the 42-month post-spill sampling time frame.

The composition of oil in the HVOM soils nine months after the spill changed considerably from the originally spilled oil. The majority of small, light components in the HVOM were greatly reduced compared to the original fresh Macondo oil (Fig. 3A and B). The content of PAHs in the fresh Macondo oil was 9022 μg/g oil while that in the HVOM soil samples was 367 μg/g oil nine months after the spill, with 2-ring naphthalenes almost completely absent (Fig. 3A). The relative abundances of 4-ring pyrenes and larger PAHs in the HVOM soil were similarly greater than the fresh oil. The content of alkanes of the fresh Macondo oil was 161,052 μg/g oil, however, that in the HVOM soils was reduced to 59,780 μg/g oil, with the light components between nC-10 and nC-15 absent (Fig. 3B). Relative abundance of nC-20 and larger alkenes in the HVOM soil was also greater than in the fresh oil.

3.2. Aboveground biomass and stem density

Total live aboveground plant biomass was significantly (p < 0.0001) lower in the HVOM than both the MDOM and reference marshes during all time periods from 9 to 42 months after the DWH oil spill (Fig. 4). However, the effect of time on aboveground biomass depended on oiling intensity (i.e., significant oiling category x sampling time interaction; p < 0.001), with moderately oiled marshes showing recovery to reference marsh levels over time while heavily oiled marshes lagged in recovery relative to reference aboveground biomass levels (Fig. 4).

The two dominant plant species, Spartina alterniflora and Juncus roemerianus, also responded to and recovered from DWH oiling differently depending on oiling intensity (Fig. 5). Oiling, sampling time, and their interaction significantly affected live aboveground biomass of both Juncus (p < 0.001, p < 0.005, p < 0.05, respectively) and Spartina (p < 0.005, p < 0.0001, p < 0.05, respectively). Live aboveground biomass of both species was significantly lower in the HVOM compared to the MDOM (p = 0.01) and reference (p = 0.0005) marshes 18 months after the spill, but Spartina recovered 24–36 months after the spill (i.e., no significant differences between oiled and reference marshes), whereas Juncus did not fully recover throughout the 42-month post-spill sampling time frame (Fig. 5). In the MDOM, live aboveground biomass of Spartina was not affected, and Juncus biomass recovered to levels similar to reference marshes 30 months after the oil spill.

Species-specific oil impacts on live stem density were similar to differences found for living aboveground biomass (Figs. 5 and 6). Both oiling (p < 0.005) and sampling time (p < 0.005) significantly influenced live stem density of Juncus, whereas Spartina live stem density was affected by oiling (p < 0.05), sampling time (p < 0.0001), and their interaction (p < 0.0001) (Fig. 6). In the HVOM, Juncus live stem density was significantly lower than in reference marshes for the entire 42-month post spill period, but Spartina live stem density recovered 18 months after the oil spill. In the MDOM, live stem density of Juncus was significantly lower during the first 18 months after the oil spill, but was similar to reference marshes thereafter. Interestingly, Spartina live stem density was significantly higher in the MDOM compared to reference marshes at 9, 18, and 24 months after the spill.

3.3. Belowground biomass

Live belowground biomass in the top 12 cm of soil was significantly lower in both the HVOM (p < 0.0001) and MDOM (p < 0.05) compared
to the RFM 18 months after the spill (Fig. 7A). Successive measurements (i.e., 24 to 42 months after the spill), analyzed in more detail at 6-cm intervals to a depth of 36 cm, further showed that live belowground biomass in the 0–6 cm soil profile was similar between moderately oiled and reference marshes, but significantly ($p < 0.0001$) lower in the HVOM than in the reference during all sampling events (Fig. 7B). The HVOM also had significantly ($p < 0.001$) lower live belowground biomass than the MDOM and reference marshes in the 6–12 cm soil increment (Fig. 7C). However, oiling did not affect live belowground biomass at deeper depths (12 to 36 cm). Regardless of oiling category, live belowground biomass, in general, decreased with soil depth in the following order: 10.5 ± 1.1 (0–6 cm), 5.3 ± 0.7 (6–12 cm), 2.4 ± 0.3 (12–18 cm), 0.93 ± 0.15 (18–24 cm), 0.43 ± 0.11 (24–30 cm) and 0.15 ± 0.04 (30–36 cm) g dm$^{-3}$ ($n = 35$). In contrast, dead biomass did not significantly change with soil depth during any sampling interval from 18 to 42 months after the spill (data not shown).

Belowground biomass accumulation in ingrowth bags during the 18 to 30 month period after the spill was not significantly affected by oiling level. Accumulation rates in the top 30 cm of the soil, averaged over the six month and one year measurement periods, were 1.13 ± 0.21, 0.99 ± 0.18, and 1.03 ± 0.22 g dm$^{-3}$ yr$^{-1}$ for the RFM, MDOM, and HVOM, respectively ($n = 14$ for each oil category).

3.4. Soil shear strength

Soil shear strength at the 0–6 cm depth was significantly ($p < 0.0001$) affected by the interaction of oiling and sampling time (Fig. 8A). Soil shear strength in the top 0–6 cm of soil in the HVOM was significantly lower than that of reference marshes throughout the entire sampling period and lower than the MDOM at 18 and 30 months after the spill. However, shear strength in the top 0–6 cm of soil was similar between the MDOM and RFM. In contrast, oiled and reference marshes had similar soil shear strengths from 6 to 12 cm soil depth (Fig. 8B); this trend also held for deeper depths (data not shown). Regardless of oiling category and time, soil shear strength in kPa decreased with soil depth in the order of 22.1 ± 0.66 (0–6 cm), 15.8 ± 0.45 (6–12 cm), 11.7 ± 0.4 (12–18 cm), 8.6 ± 0.37 (18–24 cm), 6.8 ± 0.31 (24–30 cm), and 5.7 ± 0.27 (30–36 cm) ($n = 126$). Soil shear strength was significantly ($p < 0.0001$) related to live plant belowground biomass, with approximately 40% of the variation in soil shear strength attributed to variation in live belowground biomass (Fig. 9); the greater the live belowground biomass the greater the soil shear strength.
## 3.5. Soil accretion

Soil accretion was significantly \((p < 0.0005)\) lower in the HVOM compared to the MDOM and RFM (Fig. 10), with negative values indicating that erosion was the dominant process. The HVOM eroded vertically at a rate of 68.7 ± 36.3 mm/yr between 18 and 36 months after the DWH oil spill. In contrast, soil accretion was similar among the MDOM and RFM, with vertical soil growth averaging 5.9 ± 1.46 and 3.9 ± 0.73 mm/yr, respectively.

## 4. Discussion

We found that the DWH oil spill altered measured structural and functional components of shoreline coastal salt marshes in northern Barataria Bay, LA. However, impact severity and persistence were primarily related to oiling intensity of both plant shoots and soil, as well as species-specific tolerance to oil. Analyses of the oiled surface soil documented relatively high concentrations of PAHs and alkanes nine months after the spill, indicating that residual oil was relatively toxic, although less acutely toxic than fresh Macondo crude oil and laid horizontal by tides and currents. As a result, soil shear strength and accretion of the MDOM were similar to reference marshes, with no obvious impacts to long-term marsh stability. During the 3.5-year recovery period, moderately oiled salt marsh vegetation generally recovered 2–2.5 years after the spill.

In heavily oiled marshes, almost complete mortality of vegetation was observed during the initial oiling period. During the 87-day DWH oil spill, the majority of plant shoots in the HVOM were coated with weathered DWH oil (Lin and Mendelssohn, 2012). However, regardless of the species-specific impacts, moderate oiling in the field did not kill belowground plant organs, and both Spartina and Juncus were able to recolonize. As a result, soil shear strength and accretion of the MDOM were similar to reference marshes, with no obvious impacts to long-term marsh stability. During the 3.5-year recovery period, moderately oiled salt marsh vegetation generally recovered 2–2.5 years after the spill.

MDOM marshes were significantly higher than the reference 9 to 24 months after the spill, which could have resulted from less competition for resources, such as light and nutrients, because of lower stem density and biomass of Juncus in the MDOM during this period. Also, low-level addition of petroleum hydrocarbons can be stimulatory to S. alterniflora (Li et al., 1990). These findings are supported in a greenhouse mesocosm study documenting greater sensitivity of J. roemerianus than S. alterniflora to both single and repeated oil shoot coverage with weathered DWH oil (Lin and Mendelssohn, 2012). However, regardless of the species-specific impacts, moderate oiling in the field did not kill belowground plant organs, and both Spartina and Juncus were able to recolonize. As a result, soil shear strength and accretion of the MDOM were similar to reference marshes, with no obvious impacts to long-term marsh stability. During the 3.5-year recovery period, moderately oiled salt marsh vegetation generally recovered 2–2.5 years after the spill.

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Previous research documented that high soil TPH concentrations adversely affected plant belowground organs (Lin and Mendelssohn, 1996). Four months after the DWH oil spill, Silliman et al. (2012) found that 95% of the rhizome biomass at oiled sites was dead compared to 36% in reference marshes. Similarly, in the present study, heavy marsh oiling reduced living belowground biomass (roots + rhizomes) by 84% in the top 12 cm of soil compared to reference marshes 18 months after the spill (November 2011), and remained 76% lower 42 months after the spill. Furthermore, new belowground biomass accumulation (based on ingrowth measurements) in the top 30 cm of soil (1.02 ± 0.22 g dm⁻³ yr⁻¹ in the HVOM) was approximately 20% of the existing total live belowground biomass at the same soil depth in reference marshes (5.05 ± 0.89 g dm⁻³), suggesting belowground vegetation recovery could take 5 years or longer. However, belowground biomass accumulation did not significantly differ between oiling categories, suggesting that any belowground stress due to oiling had abated by 18 to 30 months post-spill, when we measured belowground biomass accumulation. Previous studies (Mendelssohn et al., 1990; Bergen et al., 2000; Culbertson et al., 2008) indicate that heavy oiling can negatively affect marsh vegetation for a few years to as much as decades. Michel and Rutherford (2014) assessed recovery rates for 32 spills and field experiments of lightly to heavily oiled marshes. Recovery rates varied from 1 to 40 years depending primarily on climate, wave energy, oil type and volume, and cleanup treatment;
mass was one of the most important factors controlling wetland soil.

The combined effects of heavy oiling on marsh vegetation, both aboveground and belowground, resulted in significantly lower soil accretion compared to reference marshes. Marsh aboveground vegetation dissipates wave energy, which promotes sediment deposition on the surface, thus contributing to marsh vertical accretion and promoting marsh shoreline stability (Gleason et al., 1979; Stumpf, 1983; Shepard et al., 2011; Mudd et al., 2004). Furthermore, living roots and rhizomes are the most important factors determining marsh soil strength (Sasser et al., 2013). Plant roots can increase soil surface by up to 850% compared to root-free soil (Tengbeh, 1993). In the present study, the significant relationship between soil surface and roots biomass is determined by others (Silliman et al., 2012; McClenachan et al., 2013; Zengel et al., 2015). These results suggest that effects of oiling on marsh vegetation depend upon a number of factors including: oil concentration, severity of oil impact on marsh vegetation, oiling extent from shoreline, marsh location and orientation, and the energy of waves and currents. The high marsh surface erosion documented in this research for some heavily oiled shorelines has the potential to accelerate shoreline retreat, a topic of present research efforts (Deis et al., 2015).

5. Conclusion

The present research clearly shows that the DWH oil spill severely impacted coastal salt marsh vegetation structure, function, and recovery along many heavily oiled shorelines in northern Barataria Bay in the 3.5-year post-spill period. Heavy oiling killed aboveground and belowground biomass initially, which likely prevented and/or delayed recovery. Consequently, lower soil surface shear strength accelerated marsh surface erosion, which may lead to greater marsh shoreline retreat. However, marsh plants have shown resilience in moderately oiled marshes, as well as in less impacted heavily oiled marshes. Although partial shoot oiling combined with moderate soil oiling impacted aboveground structure and function in the short-term in moderately oiled marshes, oil contact did not kill belowground rhizomes, and marsh plants were capable of recovering approximately 2–2.5 years after the spill. In contrast, full recovery in heavily oiled marshes is not anticipated for 5 years or possibly longer.

Acknowledgment

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