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Planting after shoreline cleanup treatment improves salt marsh vegetation recovery following the *Deepwater Horizon* oil spill

Scott Zengel [a,*], Nicolle Rutherford [b], Brittany M. Bernik [c,1], Jennifer Weaver [d], Mengni Zhang [e], Zachary Nixon [d], Jacqueline Michel [d]

[a] Research Planning, Inc. (RPI), 247 E. 7th Avenue, Suite 200, Tallahassee, FL 32303, USA
[b] National Oceanic and Atmospheric Administration (NOAA), Office of Response and Restoration, Emergency Response Division, 7600 Sand Point Way NE, Seattle, WA 98115, USA
[c] Department of Ecology and Evolutionary Biology, Tulane University, New Orleans, LA 70118, USA
[d] Research Planning, Inc. (RPI), 1121 Park Street, Columbia, SC 29201, USA
[e] NewFields, 1349 West Peachtree Street, Suite 2000, Atlanta, GA 30309, USA

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ABSTRACT

The *Deepwater Horizon* oil spill (2010) resulted in ~100 km of heavily oiled salt marsh shorelines with severe marsh vegetation impacts. Approximately 27 km of these shorelines had marsh cleanup treatments aimed at limiting oil spread and facilitating ecological recovery. Heavy oiling impacts and disturbance from intensive cleanup treatments left marsh shorelines largely bare of live vegetation. Following operational-scale shoreline cleanup and experimental planting of *Spartina alterniflora*, we compared oiling degree and vegetation recovery among three types of heavily oiled salt marsh plots over three years: oiled control (no cleanup treatment, no planting); mechanical cleanup treatment (unplanted); and mechanical treatment coupled with planting. Nearby reference plots were used to define recovery targets and determine recovery progress. Mechanical treatment with planting showed the most improvement in oiling conditions and was most effective in re-establishing vegetation cover and dominant plant species composition approaching reference conditions. In contrast, the oiled controls and mechanical treatment plots without planting were similar and showed much slower recovery trends. Vegetation planting should be considered as a shoreline treatment or restoration approach for heavily oiled salt marshes, especially where oil impacted areas are left largely unvegetated, natural recovery is delayed, marsh shorelines are at risk of erosion, and as a possible condition for the use of intensive cleanup treatments. Vegetation planting following oil spills could be incorporated into shoreline treatment operations during emergency response as shoreline stabilization and for oil removal via phytoremediation, or as emergency restoration under the Natural Resources Damage Assessment (NRDA) process, to limit the degree and duration of natural resource impacts.

1. Introduction

The *Deepwater Horizon* oil spill (2010) was the largest marine oil spill in the U.S. to date and one of the largest worldwide: ~4.1 M barrels (560,000 metric tons) of crude oil were released into the Gulf of Mexico (McNutt et al., 2012) and at least 2113 km of shorelines were oiled (Nixon et al., 2016). Shoreline oiling included at least 1105 km of coastal wetland shorelines, primarily salt marshes dominated by *Spartina alterniflora* (smooth cordgrass) and *Juncus roemerianus* (black needlerush) (Nixon et al., 2016; Lin and Mendelssohn, 2012). Heavy oiling occurred over ~100 km of salt marsh shorelines (estimate based on datasets and methods referenced in Nixon et al., 2016). Heavy oiling was defined based on the combination of oiling band width across the shore, percent cover of oiling on the substrate or vegetation, and oiling thickness (see Michel and Rutherford, 2014; National Oceanic and Atmospheric Administration (NOAA), 2013; and Methods, below).

Negative impacts of oiling from the *Deepwater Horizon* spill on salt marsh vegetation have been described by several authors (Lin and

* Corresponding author.
E-mail addresses: szengel@researchplanning.com (S. Zengel), nicolle.r.rutherford@noaa.gov (N. Rutherford), brie.bernik@restorethegulf.gov (B.M. Bernik), jweaver@researchplanning.com, znixon@researchplanning.com, jmichel@researchplanning.com (J. Weaver), mengni.zhang2010@gmail.com (M. Zhang).
[1] Present address: Gulf Coast Ecosystem Restoration Council, 500 Poydras Street, Suite 1117, New Orleans, Louisiana 70130 USA.

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Mendelssohn, 2012; Silliman et al., 2012; Anderson and Hess, 2012; Zengel et al., 2015; Lin et al., 2016; Hester et al., 2016; Willis et al., 2016; Silliman et al., 2016). Salt marsh impacts, particularly from heavy oiling, have included vegetation dieback and denuded shorelines; reductions in plant cover, stem density, plant height, above and belowground biomass, soil shear strength, and vegetation condition; and accelerated erosion and marsh loss. Vegetation recovery in these studies has been variable, ranging from recovery in as little as 2–3 years to the absence of full recovery in heavily oiled marshes over 5 or more years.

Prior *Deepwater Horizon* studies on salt marsh vegetation have primarily examined oil impacts and recovery in the absence of shoreline cleanup treatments and restoration actions. The effects of shoreline cleanup treatments on oiled salt marsh vegetation recovery have received less attention (see Zengel et al., 2015). Likewise, the effects of restoration planting on salt marsh vegetation recovery in oiled areas following the spill have been little studied (see Bernik, 2015; Bernik et al., 2021; Johnson et al., 2018; and Cagle et al., 2020; on related topics). The effectiveness of the combination of marsh cleanup treatments and planting on vegetation recovery in heavily oiled marshes following *Deepwater Horizon* has been largely unaddressed and is the main topic of the current study.

Intensive shoreline cleanup treatments in oiled marshes are usually avoided to limit the potential for further ecological impacts caused by cleanup, such as physical damage and removal of vegetation and substrate, marsh elevation loss, and mixing of oil deeper into the soils (Pezeshki et al., 2000; Mendelssohn et al., 2012; Michel and Rutherford, 2014). However, avoiding intensive treatment and relying solely on natural recovery are not always possible under heavy oiling conditions, due to the risks of oil remobilization and spread, ongoing impacts to wildlife, and the absence of habitat recovery, particularly where there is thick (>1 cm) oiling on the marsh substrate (Baker, 1999; Michel and Rutherford, 2014). This was the case for ~27 km of salt marsh shorelines receiving varying degrees of cleanup treatment following the *Deepwater Horizon* oil spill, much of it quite intensive (treated areas were a subset of the ~100 km of heavily oiled salt marsh shorelines documented following the spill; estimates based on datasets and methods referenced in Nixon et al., 2016). Zengel et al. (2015) reported improvements in surface oiling conditions and initial vegetation recovery across two years in *Deepwater Horizon* heavily oiled salt marshes which had intensive cleanup treatments (without planting); however, vegetation recovery was incomplete and in some cases cleanup treatments mixed oil deeper into the soils and worsened shoreline erosion.

Although planting in heavily oiled marshes has been recommended for some time for substrate stabilization and enhancement of habitat recovery (see Krebs and Tanner, 1981; Baca et al., 1987; Baker, 1999), planting is rarely used following oil spills and has only been reported for a small number of studies and case histories preceding the *Deepwater Horizon* spill, sometimes with only limited or qualitative data. Planting typically results in positive influences on oiled marsh recovery (Krebs and Tanner, 1981; Seneca and Broome, 1982; Baca et al., 1987; Bergen et al., 2000; Gundlach et al., 2003), although there are anecdotal cases of planting failures as well (none published). Planting was not widely conducted in heavily oiled marshes following the *Deepwater Horizon* spill. Experimental planting of *Spartina alterniflora* by Bernik (2015) in oiled marshes shortly after shoreline cleanup treatment indicated that local wild transplants and a common commercially available cultivar performed well, while non-local wild transplants and another cultivar did not (see also Bernik et al., 2021). Working concurrently in the same study area, Zengel et al. (2015) found that planting *Spartina alterniflora* qualitatively improved vegetation recovery over one year and markedly reduced shoreline erosion relative to cleanup treatments without planting. Johnson et al. (2018) and Cagle et al. (2020) reported improvements in vegetation conditions over two months to one year in heavily oiled plots planted with *Spartina alterniflora* compared to unplanted controls; however, their studies focused on infauna and microbes with limited information reported on vegetation recovery. In these latter two studies, it is uncertain whether marsh cleanup treatments were applied prior to planting.

We report here on oiling and vegetation metrics compared among reference plots and three types of heavily oiled plots: oiled controls (no cleanup treatments, no planting); oiled and mechanically treated plots (not planted); and oiled and mechanically treated plots planted with *Spartina alterniflora*, through five years post-spill. Our experimental planting after heavy oiling and intensive shoreline cleanup treatment provides multi-year insights into the efficacy and effects of planting on oiling conditions and habitat recovery for severely impacted salt marsh shorelines. In addition to helping better understand the *Deepwater Horizon* oil spill, our findings contribute to planning, emergency response, damage assessment, and restoration efforts for future oil spills.

2. Methods

This study was conducted in the Barataria Bay "marsh treatment test area" established under the *Deepwater Horizon* emergency response, located near Bay Jimmy, Louisiana (Fig. 1). Initial heavy oiling of salt marshes in the study area began in early June 2010. By September 2010, following source control and the close of on-water oil recovery operations, oiling conditions in the study area included a continuous oiling band along the shore that was 6–13 m wide, with heavily oiled wrack and vegetation mats (oiled, dead, and laid over vegetation) overlying a 2–3 cm layer of emulsified oil on the marsh surface with 90–100% oil cover (Zengel et al., 2015; Fig. S1). Total polycyclic aromatic hydrocarbons (tPAH) averaged 833 mg/kg in the surface oil layer and 260 mg/kg in the underlying marsh soils in 2011 (Zengel and Michel, 2013; Zengel et al., 2015). The oiled control plots, mechanical treatment plots, and mechanical treatment plots with planting used in this study were all located within this same continuous and consistent band of heavy oiling.

Sampling plots for the current study were positioned on the seaward marsh edge, each spanning 5 m along shore and extending 3 m into the marsh interior. Five replicate plots were sampled for each oiling/treatment class, including reference, in each year. The oiled control plots were randomly selected as a subset of pre-existing "no treatment" plots or "set-asides" established during prior marsh treatment tests, which were randomly assigned within the study area. The oiled controls represented the only comparably oiled sites where intensive cleanup treatments were not applied in the study area. The mechanical treatment plots with and without planting were randomly established within treated locations spanning the study area.

The reference plots were randomly located within the nearest (~200 m) contiguous and comparable shoreline segment that did not have heavy persistent oiling at the onset of the marsh treatment tests, where the marsh vegetation structure remained intact during and after the spill (the marsh vegetation was not laid over or killed by oiling) (Fig. S1). There was some oiling documented in the reference plots in 2010, where three of five plots had sporadic weathered surface oil residue on the substrate that was ~0.5 m wide at the marsh edge with 1–10% oil cover and ~0.3 cm oil thickness (with no emulsified oil), a much lesser oiling degree than in the heavily oiled plots; no visible oiling was observed in any of the reference plots over 2011–2012 (Zengel et al., 2015). tPAH in the reference plot soils were 0.08 mg/kg in 2011 (Zengel et al., 2015). Although it would have been desirable to randomly intersperse the reference plots among the heavily oiled and treated plots, this was not possible due to the distribution of heavy oiling.

Mechanical cleanup treatments were applied in May–June 2011 at operational scale as a part of the wider oil spill response (avoiding the oiled control plots and reference sites). Mechanical treatments in the study area were applied using various tools attached to long-reach hydraulic booms deployed from floating shallow-draft barges or large airboat platforms. Mechanical treatments included mechanized grappling to remove loose oiled wrack and vegetation debris; mechanical raking and cutting to remove oiled vegetation mats (leaving rooted plant stubble in place); and mechanical raking, scraping, or "squeegeeing" to

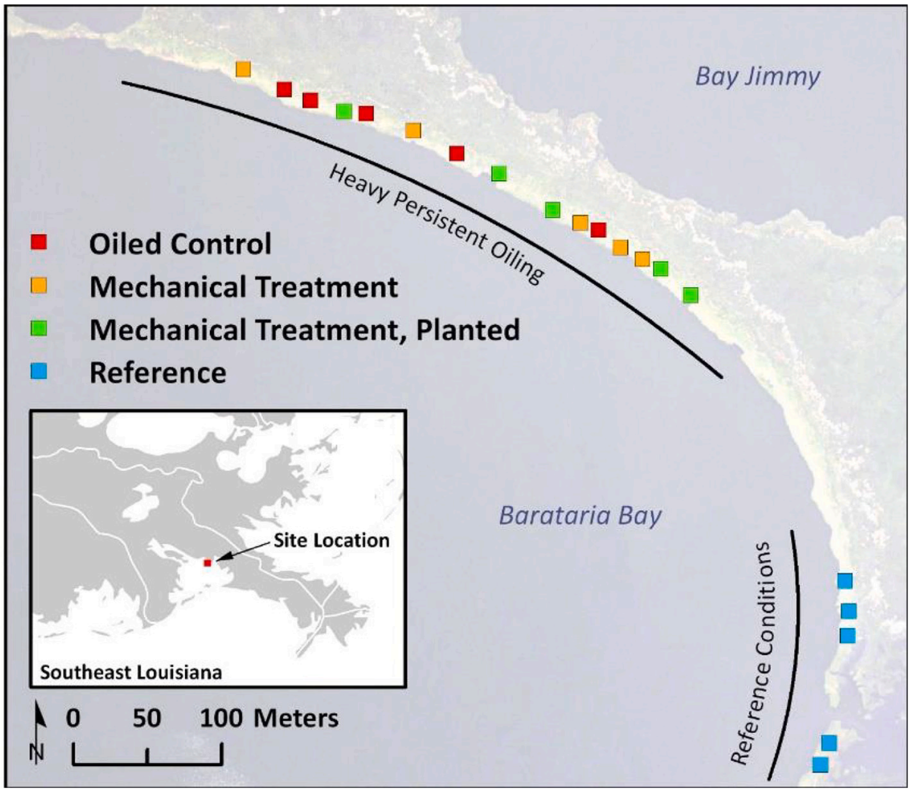

Fig. 1. Study area map with locations of sampling plots by oiling/treatment class, including reference sites. Oiled control plots were heavily oiled with no cleanup treatments or planting.

remove thick emulsified oil from the marsh substrate (Zengel and Michel, 2013; Zengel et al., 2015; Fig. S2). The mechanical treatments were applied in the sequence listed above and entirely removed the oiled wrack, removed or reduced the oiled vegetation mats, reduced the distribution and thickness of the emulsified oil layer, and converted the dominant surface oiling condition from emulsified oil to a more weathered surface oil residue (Zengel and Michel, 2013; Zengel et al., 2015). Vegetation planting in the mechanically treated and planted plots involved hand-planting individual bare root *Spartina alterniflora* stems at a density of ~2–3 stems m^{-2} shortly following shoreline cleanup treatments (Bernik, 2015; Bernik et al., 2021; Fig. S3). Prior to planting, the plots were largely devoid of live vegetation due to oil impacts and cleanup treatments. A transplanted local wild *Spartina alterniflora* variety native to Bay Jimmy, Louisiana was used for this study. No fertilizer was applied. Planting was completed in summer and early fall 2011.

Sampling for this study was conducted in September/early October over three years, from 2013 to 2015, at three to five years following initial oiling and two to four years following mechanical treatments and planting. Surface and subsurface oiling descriptions, including oil cover, thickness, and character were based on standardized shoreline assessment methods and terminology applied within each plot (National Oceanic and Atmospheric Administration (NOAA), 2013). Subsurface oiling was visually examined by digging at least two to three shovel test pits per plot to ~20 cm depth and describing oiling distribution, thickness, and character. Shovel test pit locations included at least two haphazardly positioned locations within each plot and, where applicable, one or more selected locations based on geomorphic, surface oiling, and vegetative cues. Surface oiling cover and vegetation cover by species and in total were estimated across each plot, using both visual cover estimation charts and repeated quartering of the plots as needed. Cover estimates were initially made by two independent observers who then compared estimates and arrived at a mutually agreed-upon value. *Spartina alterniflora* vegetation height was estimated using a vertical profile rod marked in cm increments.

Subsurface soil samples were collected for chemical analysis using 15 cm diameter cores taken to 10 cm depth, specifically excluding oil and oiled vegetation debris on the marsh surface, which were scraped aside prior to sampling. Therefore, oil chemistry results represent oil concentrations in the soils (not oil on the marsh surface). One soil core was collected from the center of each plot per sampling event. tPAH in marsh soils were determined using GC/MS-SIM (gas chromatography/mass spectrometry in selective ion monitoring mode) based on modified EPA Method 8270D. tPAH included the sum of 45 PAHs, including alkylated homologues, presented as mg/kg. Chemical analyses were conducted by the Response and Chemical Assessment Team from the Louisiana State University Department of Environmental Sciences.

All parameters were plotted by oiling/treatment class per year as means ±1 standard error (SE). Two-way mixed ANOVAs were used for all statistical analyses with oiling/treatment class as the between-subjects factor and year as the within-subjects factor. Data were not transformed. Greenhouse-Geiser corrections were applied in cases where the sphericity assumption was violated according to Mauchly's test. Effects sizes were estimated using generalized eta-squared (η^2_G). Post-ANOVA pairwise comparisons were made using Tukey's test, and were mainly considered only when the ANOVA results indicated potential differences. We generally considered statistical significance as $p \leq 0.10$, and effects size thresholds as $\eta^2_G = 0.20$ (small effect), $\eta^2_G = 0.50$ (medium effect), and $\eta^2_G = 0.80$ (large effect); however, based on recent guidance (Wasserstein et al., 2019; Smith, 2020), we did not use these values as cutoff points, choosing instead to form our overall interpretations based on the combination of the plotted data, including visual trends and tendencies in the data, and the statistical results. Analyses were conducted in R version 3.6.3. ANOVA test statistics, degrees of freedom, *p*-values, effects sizes, and summaries for pairwise comparisons are reported in the figure captions with the corresponding data figures. Descriptive statistics, ANOVA tables, and post-ANOVA pairwise test results are reported in full in Table S1.

3. Results and discussion

3.1. Oiling conditions

Appreciable differences in surface oil cover (%) were observed among oiling/treatment classes (Fig. 2, Table S1). Surface oiling was not observed in the reference plots during 2013–2015 (0% surface oil cover in all years). The oiled controls and the mechanically treated plots without planting had similar surface oil cover (means ranging from 26 to 45% for individual years), whereas the mechanically treated plots with planting had much less surface oiling (means ranging from 5 to 11% for individual years). Across the heavily oiled plots in all years, surface oiling character mainly consisted of a weathered crust-like oil residue (oil mixed with sediment), although oiled vegetation mats and emulsified oil were also present on the marsh surface in the oiled controls in 2013. Surface oil thickness was mostly ≤1 cm across the heavily oiled plots; however, in 2013 the oiled controls and mechanically treated plots without planting had areas with thicker surface oiling, >1 cm, some of which persisted into 2014. By 2015, all the heavily oiled plots were limited to surface oil residue with oiling thickness ≤1 cm.

Subsurface oiling was not visually observed in the reference plots during 2013–2015. Subsurface oiling was most severe in the oiled controls, where observations included buried oiled vegetation mats and layers of emulsified oil up to several cm thick which persisted into 2015, extending to soil depths of 15–18 cm or more in some locations (Fig. S4). By 2015 the mechanically treated plots without planting mainly had oil residue mixed into the soils, with small amounts of emulsified oil. In 2015, the mechanically treated and planted plots had limited subsurface oiling (three plots had no visible subsurface oiling and two plots had minor amounts of patchy oil residue mixed into the soils, but without emulsified oil). Apparent mechanisms leading to subsurface oiling included: oil penetration via animal burrows (such as fiddler crab burrows) and older plant shoot and root cavities; oil burial by accumulated soils or sediments; mixing of oil into the substrate during mechanical treatments; and combinations of these factors.

Small differences in soil tPAH values were observed among years, but not among oiling/treatment classes (Fig. 3, Table S1). Subsurface tPAH values tended to decline over time across oiling/treatment classes, particularly for 2013–2014. The reference plots generally had low levels of tPAH over 2013–2015 (means ranging from 0.2 to 2.3 mg/kg for individual years). tPAH in the reference plots were above reported background values in 2013 (2.3 mg/kg), but similar or close to reported background values in 2014 and 2015 (0.2 and 0.4 mg/kg, respectively). Turner et al. (2014) and Rouhani et al. (2017) reported background tPAH values during the *Deepwater Horizon* spill of 0.2 mg/kg and 0.3 mg/kg, respectively. The elevated reference levels in 2013 were likely due to initial sporadic light oiling in some of the reference plots during the spill. There were some particularly high, though variable, tPAH values from the heavily oiled plots in 2013 (means ranging from 21.2 to 106.3 mg/kg across oiled treatment classes), especially for the mechanically treated plots without planting (106.3 mg/kg), which may reflect heterogeneous mixing of oil into the soils during treatment. By 2015, the mechanically treated and planted plots (0.8 mg/kg) were approaching reported background and reference values, while the oiled controls (1.7 mg/kg) and mechanically treated plots without planting (2.9 mg/kg) were generally lower than in 2013, yet still somewhat elevated compared to background levels. The absence of differences in subsurface tPAH values among oiling/treatment classes, as well as apparent contrasts with the visual oiling assessments, may be related to several factors, including: high variability in tPAH distribution in the soils; the limited soil sampling conducted for chemical analysis (one core per plot per year); degradation of tPAH over time; and burial of oiling exceeding the depth of the cores. To the latter point, a subsurface grab sample from a buried emulsified oil layer in one of the oiled control plots in 2015, taken from a soil depth of 15–17 cm in one of the shovel test pits, had a tPAH value of 458 mg/kg. This value was similar in order of magnitude to tPAH in surface oil samples collected in 2011 from the same study area (505 to 833 mg/kg; Zengel and Michel, 2013).

Overall, oiling conditions in the heavily oiled sites were most improved for the plots with mechanical treatment and planting. The improvements in oiling conditions in the planted plots may be attributed to multiple years of *Spartina alterniflora* rhizome and root growth and new shoot emergence physically loosening and breaking up the residual oiling, resulting in smaller pieces of oil residue with more exposed surface area, thereby enhancing oil weathering, degradation, and

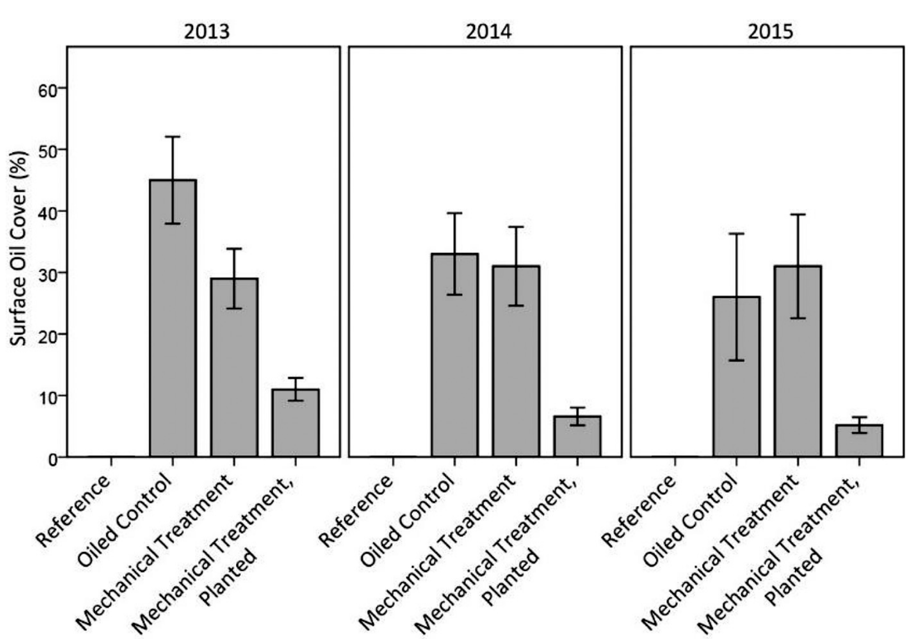

Fig. 2. Surface oil cover (%) on the marsh substrate, 2013–2015. Data are means ±1 SE. $N = 5$ for all oiling/treatment classes in each year. Surface oil cover differed among oiling/treatment classes with a medium-large degree of effects ($F_{3,16} = 14.168$, $p = 0.0001$, $\eta^2_G = 0.654$). Surface oil cover did not differ among years ($F_{1.16,18.57} = 2.677$, $p = 0.1150$, $\eta^2_G = 0.046$) or for the interaction of oiling/treatment class and year ($F_{3.48,18.57} = 1.868$, $p = 0.1640$, $\eta^2_G = 0.092$). Pairwise differences among oiling/treatment classes were observed for: reference versus the oiled controls and mechanical treatment plots without planting ($p = 0.0003$ and 0.0011, respectively); and mechanical treatment plots with planting versus the oiled controls and mechanical treatment plots without planting ($p = 0.0031$ and 0.0123, respectively). Reference and mechanical treatment plots with planting were not different ($p = 0.6395$); nor were the oiled controls and mechanical treatment plots without planting ($p = 0.9030$).

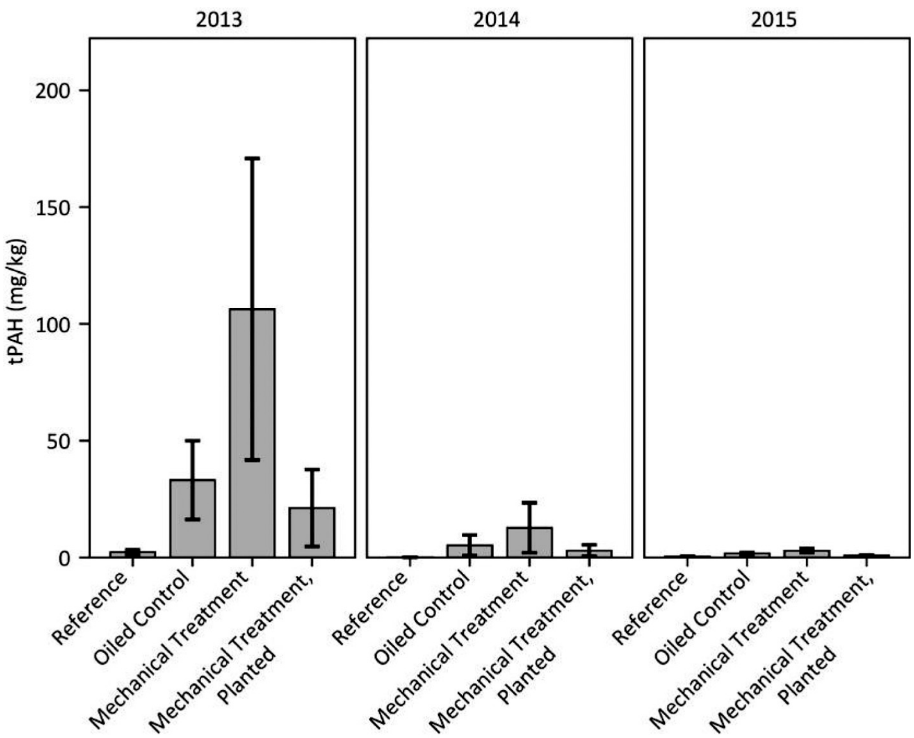

Fig. 3. Total polycyclic aromatic hydrocarbons (tPAH) in subsurface marsh soils, 2013–2015. Data are means ±1 SE. $N = 5$ for all oiling/treatment classes in each year. tPAH did not differ among oiling/treatment classes ($F_{3,16} = 1.832$, $p = 0.1820$, $\eta^2_G = 0.122$). tPAH differed among years with a less than small effects size ($F_{1.03,16.56} = 5.181$, $p = 0.0350$, $\eta^2_G = 0.162$), but did not differ for the interaction of oiling/treatment class and year ($F_{3.1,16.56} = 1.659$, $p = 0.2140$, $\eta^2_G = 0.156$).

physical removal. More subtle phytoremediation effects, including soil oxidation and enhanced microbial activity, may also have played a role (Lin and Mendelssohn, 1998, 2008, 2009; Cagle et al., 2020). Indirect phytoremediation effects may have included improved recovery of infauna populations and increased burrowing and bioturbation (increased soil aeration, flushing, etc.), facilitated by planting and accelerated vegetation recovery (see Fleeger et al., 2015, 2018, 2019; Zengel et al., 2016; Johnson et al., 2018).

In contrast, surface oiling conditions in the mechanically treated plots without planting were not noticeably improved versus the oiled controls over the course of our study. Early improvements in surface oiling with mechanical treatment versus oiled controls were reported in 2011–2012 (Zengel et al., 2015) and seemed to marginally continue into 2013, but by the end of the study period (2015), surface oiling cover was similar in the oiled controls and mechanically treated plots without planting. Natural oil weathering and removal mechanisms, increasing vegetation cover, and oil burial may have contributed to declines in residual surface oiling in the oiled controls over time (oil burial in the oiled controls seemed particularly associated with *Paspalum vaginatum* vegetation cover, discussed below). The shorter-term improvements in subsurface oiling in the mechanical treatment plots without planting relative to the oiled controls can likely be attributed to the removal or reduction of the oiled vegetation mats and emulsified oil layers by mechanical treatment and the subsequent burial of this same material that was not removed from the oiled controls, although oil was also mixed into the soils during mechanical treatment. Regardless, oiling conditions were still initially improved (or were improved more quickly) by mechanical treatment alone relative to the oiled controls, but not to the same degree as for mechanical treatment plus planting. In total, oiling conditions in both the mechanically treated plots without planting and the oiled controls were still quite distinct from the reference and planted plots during our study, pointing to the likely importance of mechanical treatment coupled with planting for oil removal and degradation.

3.2. *Vegetation metrics*

Notable differences in total vegetation cover (all species combined) were observed among oiling/treatment classes, as were smaller differences among years and for the interaction of oiling/treatment class and year (Fig. 4, Table S1). Total vegetation cover values across all years were similar for the reference and mechanically treated plots with planting, with means ranging from 88 to 99% for individual years. Total vegetation cover values for the oiled controls and mechanical treatment plots without planting were also comparable to each other each in all years, and were lower than in the reference and planted plots, particularly in 2013 and mostly in 2014 as well (means were 49% and 43% in 2013, respectively, roughly half of those in the reference and planted plots). By 2015, total vegetation cover values had increased in both the oiled controls and mechanical treatment plots without planting to the point that all oiling/treatment classes were similar, including the reference plots, indicating a degree of vegetation recovery across all the heavily oiled plots.

Although total vegetation cover is an important metric, especially when multiple species are present, plant species composition is also an important consideration. Salt marshes in the region are typically dominated by *Spartina alterniflora* and in some cases *Juncus roemerianus*, and a return to similar species dominance would be an indicator of habitat recovery. In addition, differences in species composition may underlie important differences in marsh structure and function (such as vegetation stature and depth of rooting in relation to shoreline resilience and erosion). In terms of relative cover, the reference plots showed clear dominance by *Spartina alterniflora*, followed by smaller but noticeable amounts of *Juncus roemerianus*, and minor occurrences of *Spartina patens* and *Distichlis spicata*, typical for salt marsh shorelines in the region (Chabreck, 1970; Visser et al., 1998) (Fig. 5). The mechanical treatment plots with planting were also dominated by *Spartina alterniflora*, and though missing *Juncus roemerianus*, had minor occurrences of *Spartina patens*, *Distichlis spicata*, *Avicennia germinans* seedlings, and *Paspalum*

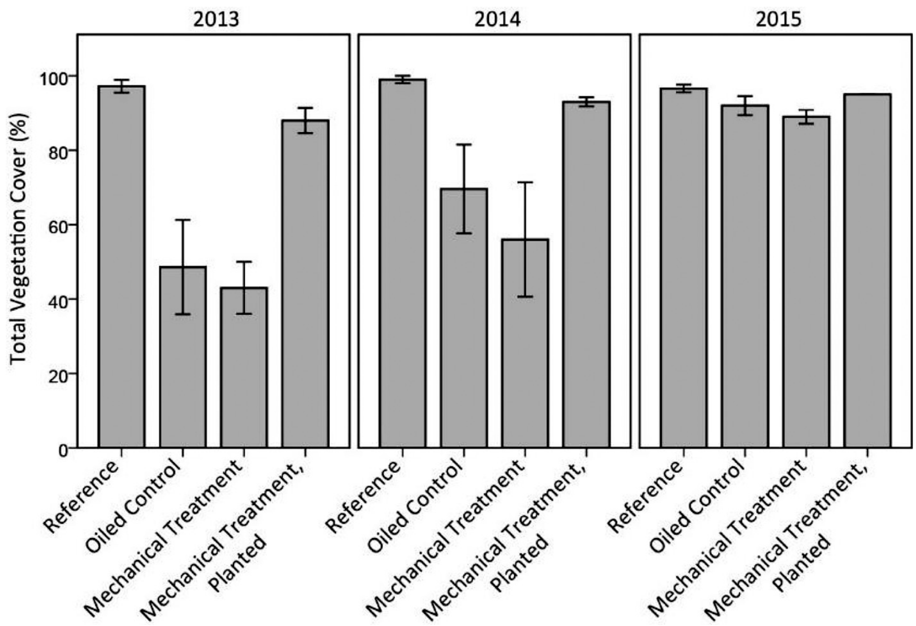

Fig. 4. Total vegetation cover, 2013–2015. Data are means ±1 SE. $N = 5$ for all oiling/treatment classes in each year. Total vegetation cover differed among oiling/treatment classes with a medium degree of effects ($F_{3,16} = 11.971$, $p = 0.0002$, $\eta^2_G = 0.509$); among years with a small degree of effects ($F_{2,32} = 13.927$, $p = 0.0000$, $\eta^2_G = 0.319$); and for the interaction of oiling/treatment class and year with a small degree of effects ($F_{6,32} = 3.777$, $p = 0.0060$, $\eta^2_G = 0.276$). Overall pairwise differences among oiling/treatment classes were observed for: reference versus the oiled controls and mechanical treatment plots without planting ($p = 0.0051$ and 0.0006, respectively); and mechanical treatment plots with planting versus the oiled controls and mechanical treatment plots without planting ($p = 0.0266$ and 0.0030, respectively). Reference and mechanical treatment plots with planting were not different ($p = 0.8473$); nor were the oiled controls and mechanical treatment plots without planting ($p = 0.7093$). For oiling/treatment class differences within year, the same pattern above was observed in 2013 for all comparisons. A very similar pattern was observed in 2014, though it was not as distinct for each comparison. Pairwise oiling/treatment class differences were not observed in 2015.

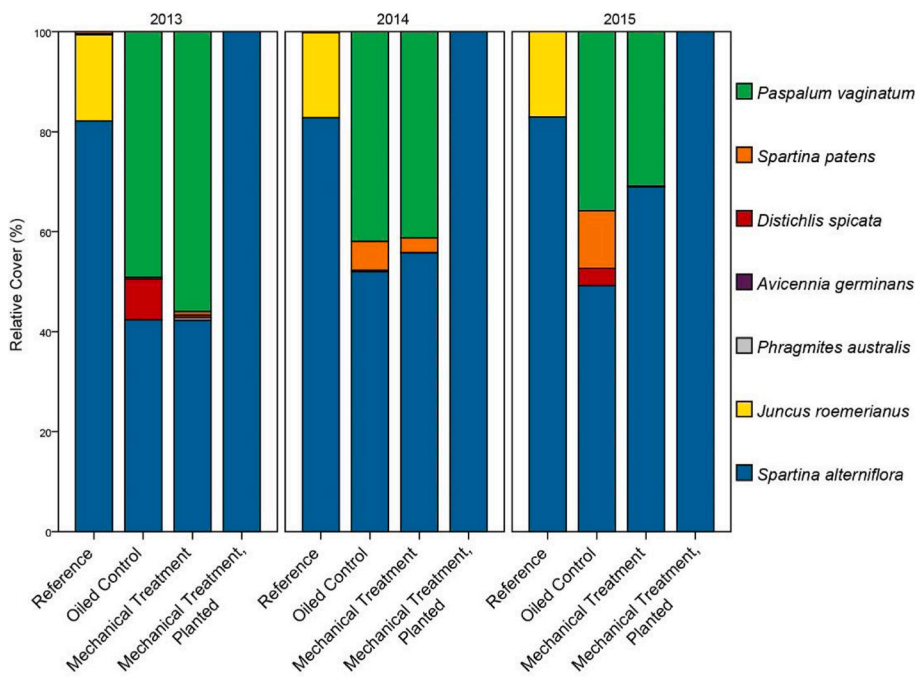

Fig. 5. Vegetation species composition by relative cover, 2013–2015.

vaginatum. In contrast, the oiled controls and mechanical treatment plots without planting were co-dominated by *Spartina alterniflora* and *Paspalum vaginatum*, along with smaller contributions from *Spartina patens* and *Distichlis spicata*. The relative cover of *Paspalum vaginatum* across all years in the oiled controls and mechanically treated plots without planting was a noticeable contrast to the reference and planted plots, especially since *Paspalum vaginatum* is typically a secondary species found in lower salinity coastal marshes in the region, but not in salt marshes (Chabreck, 1970; Visser et al., 1998).

Looking more quantitatively at individual species, notable differences in *Spartina alterniflora* cover were observed among oiling/treatment classes, as were minor differences among years and for the interaction of oiling/treatment class and year (Fig. 6, Table S1). *Spartina alterniflora* cover was comparable across all years in the reference and mechanically treated plots with planting (means ranging from 79 to 95% for individual years), indicating recovery for this metric in the planted areas. In contrast, *Spartina alterniflora* cover values in the oiled controls and mechanically treated plots without planting were lower overall, though they did improve with time, so that differences were not as distinct in all cases in 2015, although mean values still tended to be lower (means were 44% and 61% in 2015, respectively). The mechanical treatment plots without planting improved across all years, whereas the

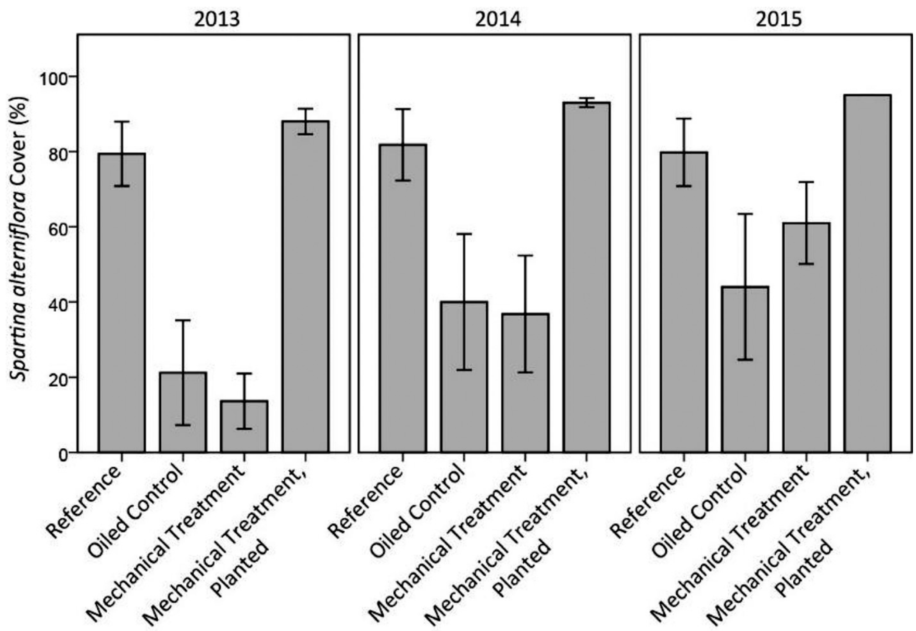

Fig. 6. *Spartina alterniflora* vegetation cover, 2013–2015. Data are means ±1 SE. $N = 5$ for all oiling/treatment classes in each year. *Spartina alterniflora* cover differed among oiling/treatment classes with a medium degree of effects ($F_{3,16} = 7.288$, $p = 0.0030$, $\eta^2_G = 0.552$); among years with a less than small degree of effects ($F_{1.46,23.34} = 19.964$, $p = 0.0000$, $\eta^2_G = 0.110$); and for the interaction of oiling/treatment class and year with a less than small degree of effects ($F_{4.38,23.34} = 5.844$, $p = 0.0020$, $\eta^2_G = 0.097$). Overall pairwise differences among oiling/treatment classes were observed for: reference versus the oiled controls and mechanical treatment plots without planting ($p = 0.0423$ and 0.0547, respectively); and mechanical treatment plots with planting versus the oiled controls and mechanical treatment plots without planting ($p = 0.0093$ and 0.0122, respectively). Reference and mechanical treatment plots with planting were not different ($p = 0.8711$); nor were the oiled controls and mechanical treatment plots without planting ($p = 0.9991$). For oiling/treatment class differences within year, the same pattern above was observed in both 2013 and 2014 for all comparisons. Although the general pattern continued into 2015, pairwise oiling/treatment class differences were not as distinct or were not detected in most cases, the exception being the oiled controls versus the planted plots ($p = 0.0283$). Changes within oiling/treatment classes among years involved the oiled controls, which improved over 2013–2014 ($p = 0.0131$), and the mechanical treatment plots without planting, which improved over both 2013–2014 ($p = 0.0021$) and 2014–2015 ($p = 0.0013$).

oiled controls only improved over 2013–2014, indicating a possible slight benefit to vegetation recovery with mechanical treatment. Still, mechanical treatment coupled with planting clearly had the fastest and best overall outcome for the return of *Spartina alterniflora* cover to impacted areas.

Although the return of *Spartina alterniflora* cover was achieved in the mechanical treatment plots with planting, appreciable differences in *Spartina alterniflora* vegetation height were observed between reference and mechanical treatment plots with planting (Fig. 7, Table S1). *Spartina alterniflora* height in the planted plots had not recovered as of 2015, with mean annual plant heights averaging 17 cm taller in the reference plots in the last year of our study. Even though *Spartina alterniflora* was recovering most effectively in the planted plots, vegetation height indicated incomplete recovery for *Spartina alterniflora* in the planted areas, which persisted throughout the study period.

Differences in *Juncus roemerianus* cover were also observed among oiling/treatment classes (Fig. 8, Table S1). Although *Juncus roemerianus* cover was variable among the reference plots, mean *Juncus roemerianus* cover was consistent across years (means 17%), while in comparison there was little to no *Juncus roemerianus* in the heavily oiled plots, including none in the planted plots. Poor recovery of *Juncus roemerianus* in heavily oiled areas is consistent with prior *Deepwater Horizon* studies (Lin and Mendelssohn, 2012; Lin et al., 2016). *Juncus roemerianus* is sensitive to oiling, more so than *Spartina alterniflora*, and may be one of

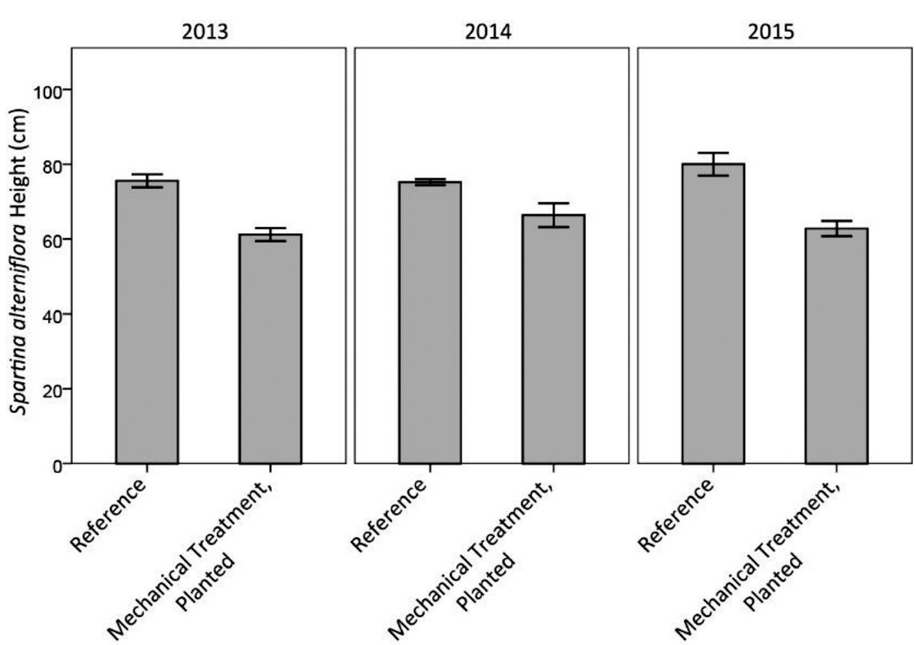

Fig. 7. *Spartina alterniflora* vegetation height for reference versus mechanical treatment with planting, 2013–2015. Data are means ±1 SE. $N = 5$ for each oiling/treatment class in each year. *Spartina alterniflora* height differed among the reference and mechanical treatment plots with planting with a medium-large degree of effects ($F_{1,8} = 33.107$, $p = 0.0004$, $\eta^2_G = 0.691$). *Spartina alterniflora* height did not differ among years ($F_{2,16} = 1.45$, $p = 0.2640$, $\eta^2_G = 0.077$). There was possibly some interaction of oiling/treatment class and year with a less than small degree of effects ($F_{2,16} = 2.631$, $p = 0.1030$, $\eta^2_G = 0.131$); however, oiling/treatment class differences were still observed in each year.

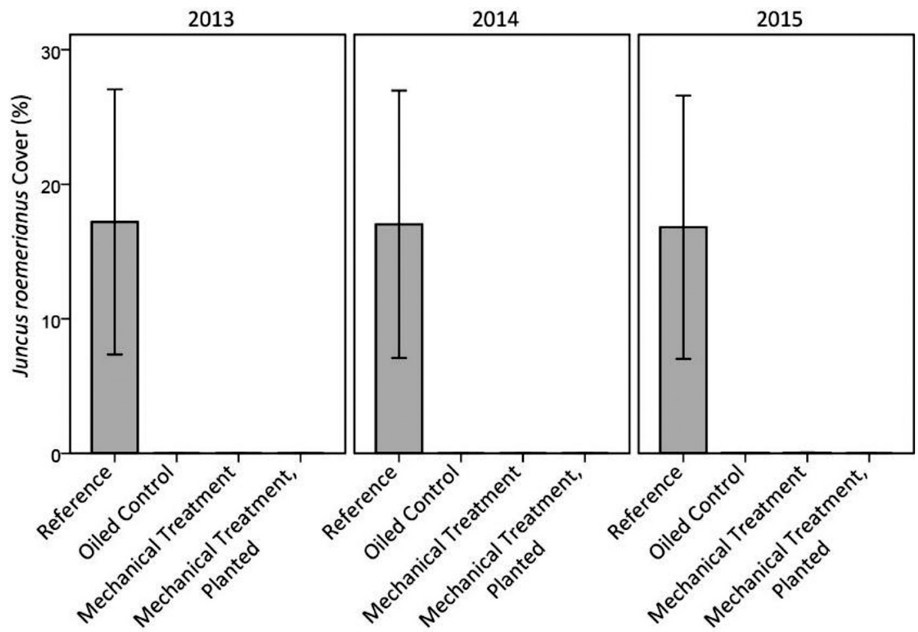

Fig. 8. *Juncus roemerianus* vegetation cover, 2013–2015. Data are means ±1 SE. $N = 5$ for all oiling/treatment classes in each year. *Juncus roemerianus* cover differed among oiling/treatment classes with a small-medium degree of effects ($F_{3,16} = 2.975$, $p = 0.0630$, $\eta^2_G = 0.358$). *Juncus roemerianus* cover did not differ among years ($F_{1.24,19.81} = 0.332$, $p = 0.6180$, $\eta^2_G = 0.000$) or for the interaction of oiling/treatment class and year ($F_{3.71,19.81} = 0.514$, $p = 0.7140$, $\eta^2_G = 0.000$).

the slower species to recover from oiling (Lin and Mendelssohn, 2009, 2012; Anderson and Hess, 2012; Michel and Rutherford, 2014; Pezeshki and DeLaune, 2015; Lin et al., 2016). The dearth of *Juncus roemerianus* in the heavily oiled plots through 2015 indicates that recovery for this species may lag substantially behind that of *Spartina alterniflora*. The absence of *Juncus roemerianus* further indicates lack of full recovery in the planted areas despite the return of *Spartina alterniflora* cover. Where *Juncus roemerianus* is a component of the salt marsh flora, planting of this species could also be considered, given appropriate soil oiling levels and habitat conditions. Experimental planting of *Juncus roemerianus* was attempted following the *Deepwater Horizon* spill on a small scale, but was not successful (D.R. Deis, personnel communication). Accordingly, more work is required in this area. It may be that initial planting of *Spartina alterniflora* is more effective for shoreline stabilization, oil removal, and restoration, followed by later planting or natural recruitment of *Juncus roemerianus* into areas where it would normally occur.

Finally, differences in *Paspalum vaginatum* cover were observed among oiling/treatment classes (Fig. 9, Table S1). *Paspalum vaginatum* cover values were variable but similar for the oiled controls and mechanically treated plots without planting, and relatively consistent across years (means ranging from 25 to 35% for individual years for the oiled controls), whereas the reference and mechanically treated plots

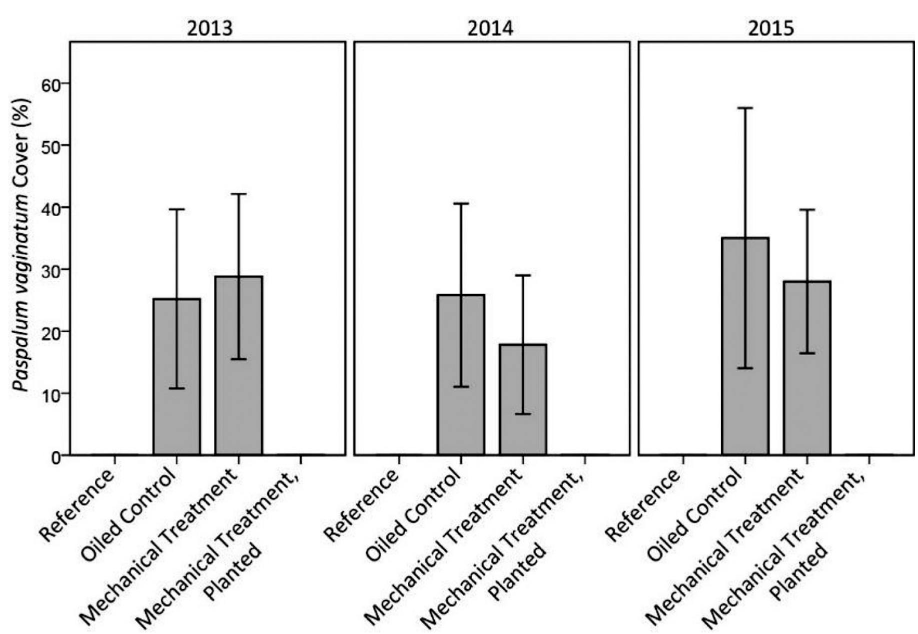

Fig. 9. *Paspalum vaginatum* vegetation cover, 2013–2015. Data are means ±1 SE. $N = 5$ for all oiling/treatment classes in each year. *Paspalum vaginatum* cover differed among oiling/treatment classes with a small degree of effects ($F_{3,16} = 2.679$, $p = 0.0820$, $\eta^2_G = 0.294$). *Paspalum vaginatum* cover did not differ among years ($F_{2,32} = 0.843$, $p = 0.4400$, $\eta^2_G = 0.009$) or for the interaction of oiling/treatment class and year ($F_{6,32} = 0.527$, $p = 0.7830$, $\eta^2_G = 0.017$).

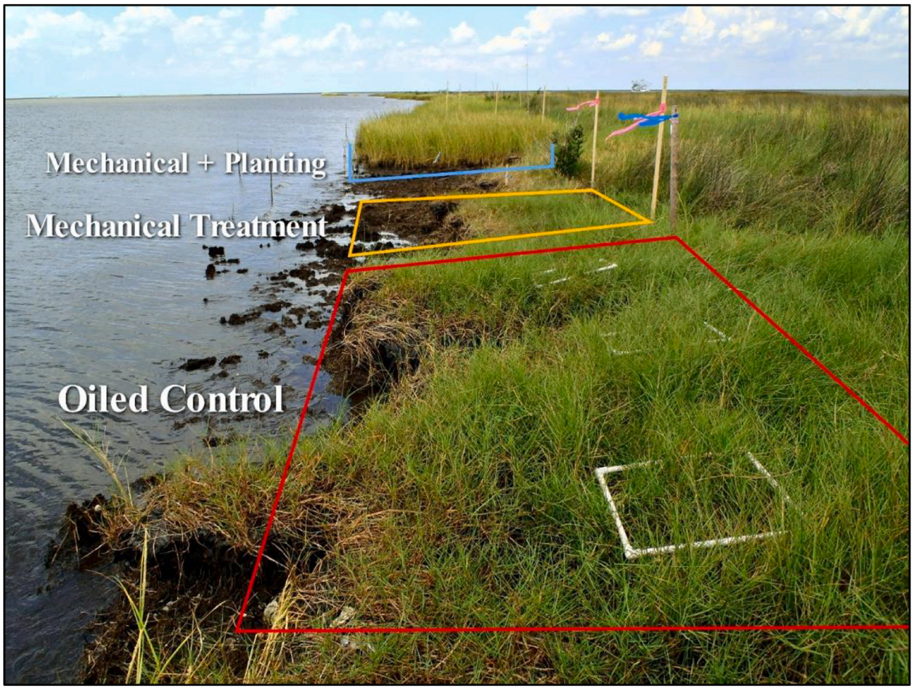

Fig. 10. Summary plot conditions across oiling/treatment classes: foreground (red outline), oiled control plot (no cleanup treatment or planting), dominant vegetation *Paspalum vaginatum*; middle (orange outline), mechanical treatment plot without planting, dominant vegetation *Paspalum vaginatum*; background (blue outline), mechanical treatment plot with planting, dominant vegetation *Spartina alterniflora*. Note the differences in vegetation growth form and height, as well as apparent shoreline erosion. Photo taken September 2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with planting had little to no *Paspalum vaginatum* for the duration of the study, with this species never being observed in the reference plots. Though not a typical salt marsh species, *Paspalum vaginatum* can be a disturbance-associated coastal marsh species, displaying increased cover values and dominance following various sources of marsh disturbance (Shiflet, 1963; Miller et al., 2005; Bhattacharjee et al., 2007). This species may have been able to colonize impacted areas due to unvegetated substrates resulting from oiling and reduced salinities following freshwater releases enacted in response to the spill (Bianchi et al., 2011; Powers et al., 2017). Although *Paspalum vaginatum* provided vegetation cover in impacted areas, its presence and dominance in some areas are not indicative of desirable marsh conditions or full vegetation recovery. For instance, due to its shorter stature, sprawling growth form, and shallower rooting, *Paspalum vaginatum* would not be expected to stabilize shorelines as well as *Spartina alterniflora* or provide equivalent habitat structure or cover. *Paspalum vaginatum* was also often associated with buried oil layers (Fig. S4). This species recruited on top of the oiled vegetation mats and surface oil, displayed shallow rooting, spreading by surface runners, and accumulated soils on top of the oil. In contrast, both planted and naturally occurring *Spartina alterniflora* tended to spread by rhizomes and grow up through the surface oil layers with new shoots. Periods of higher salinity could perhaps hasten the decline and replacement of *Paspalum vaginatum* in the study area with time, as could active vegetation management (such as removal and re-planting with *Spartina alterniflora*).

Both *Spartina alterniflora* and *Juncus roemerianus* were originally present and appeared to be dominant prior to the spill in the heavily oiled plots, based on the initial composition of the oiled vegetation mats and the intact vegetation landward of the plots. Therefore, the pre-spill vegetation composition in the heavily oiled plots was likely comparable to the reference area. The observed differences in marsh species composition in the oiled controls and mechanical treatment plots without planting may have been a result of several factors: the nearly complete vegetation dieback resulting from heavy oiling; differing sensitivities to oiling and physical disturbance among plant species (*Juncus roemerianus* being more sensitive); colonization by disturbance-associated species (including *Paspalum vaginatum* and *Distichlis spicata*; Bertness and Ellison, 1987); and initial plant re-colonization during a time of lower salinities associated with freshwater releases (allowing *Paspalum vaginatum* to recruit but perhaps also favoring *Spartina patens* and *Distichlis spicata*; Chabreck, 1970; Visser et al., 1998; see also the 2011–2012 relative cover values in Zengel et al., 2015). Similar initial recruitment and dominance of *Distichlis spicata* in heavily oiled and denuded salt marsh sites were observed in part by Zengel et al. (2015), by Johnson et al. (2018) and Cagle et al. (2020) in their unplanted control plots, as well as by Beland et al. (2016) in their remote sensing study. Planting in our study had an obvious positive effect on vegetation cover and dominance by *Spartina alterniflora*, although *Spartina alterniflora* height and perhaps other metrics were still below reference values, indicating that vegetation recovery was ongoing (see Lin et al., 2016; Silliman et al., 2016; and Fleeger et al., 2018 regarding the slow recovery of belowground biomass in heavily oiled salt marshes after the spill).

Overall, through four years following treatment applications, mechanical treatment alone did not appear to greatly improve vegetation recovery in terms of dominant plant cover and species composition relative to the oiled controls, and neither the oiled controls nor mechanically treated plots without planting were approaching vegetation recovery relative to reference conditions. In contrast, mechanical treatment coupled with planting was effective in improving vegetation recovery, resulting in vegetation cover and *Spartina alterniflora* species dominance comparable to the reference plots within two years following planting, even though full vegetation recovery and total marsh ecosystem recovery may still be ongoing.

4. Conclusions

In summary, planting following mechanical treatment improved both oiling conditions and vegetation recovery relative to mechanical treatment without planting and the oiled controls (see Fig. 10 for a visual summary). In addition, for most of the metrics evaluated, planted plots had reached or were approaching conditions in the nearby reference plots, indicating that recovery was well underway in the planted plots. Although not addressed in this study, planting may also have added benefits of reducing marsh shoreline erosion following spills (Zengel et al., 2015) and enhancing marsh invertebrate and microbial recovery (Zengel et al., 2016; Johnson et al., 2018; Fleeger et al., 2019; Cagle et al., 2020). Accordingly, we recommend that planting be considered for oil spills with heavy marsh oiling and as a possible condition for application of intensive marsh cleanup methods because of the effectiveness of planting in removing oil, mitigating damage to the shoreline due to substrate loss, and enhancing habitat recovery. This may include planting heavily oiled and impacted sites without preceding intensive cleanup treatments. Planting is especially important where oil impacted areas are left largely unvegetated, natural recovery may be delayed, background erosion rates are high, or wetland loss is a major concern, as is the case in coastal Louisiana and other regions. There are two authorities under which planting could be applied following spills: (1) under emergency response, incorporating planting into the oiled shoreline treatment process as shoreline stabilization and for oil removal via phytoremediation; or (2) as emergency restoration under the NRDA process, to limit the degree and duration of damages to natural resources. Additional planting studies following oil spills are needed to examine variation among spills, oil types, oiling levels, cleanup methods, timing (post-oiling and cleanup), site conditions, plant species, other vegetation metrics (including belowground biomass), and marsh-associated biota. Post-spill comparisons of planting methods and materials are also needed (e.g., wild transplants versus nursery stock, bare root versus containerized plantings, clustered versus evenly spaced plantings, and comparisons among different plant species, varieties, and species groupings; see Bernik, 2015; Bernik et al., 2021; Silliman et al., 2015; Renzi et al., 2019). Finally, reiterating and expanding on Zengel et al. (2015), oiled control sites (i.e., no treatment "set-asides"), as well as reference areas, are essential for evaluating shoreline cleanup treatment and restoration effectiveness and ecological effects following oil spills. We recommend their use when applying intensive or alternative methods, including planting.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2021.106288.

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