Degradation and resilience in Louisiana salt marshes after the BP–*Deepwater Horizon* oil spill

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More than 2 y have passed since the BP–*Deepwater Horizon* oil spill in the Gulf of Mexico, yet we still have little understanding of its ecological impacts. Examining effects of this oil spill will generate much-needed insight into how shoreline habitats and the valuable ecological services they provide (e.g., shoreline protection) are affected by and recover from large-scale disturbance. Here we report on not only rapid salt-marsh recovery (high resilience) but also permanent marsh area loss after the BP–*Deepwater Horizon* oil spill. Field observations, experimental manipulations, and wave-propagation modeling reveal that (*i*) oil coverage was primarily concentrated on the seaward edge of marshes; (*ii*) there were thresholds of oil coverage that were associated with severity of salt-marsh damage, with heavy oiling leading to plant mortality; (*iii*) oil-driven plant death on the edges of these marshes more than doubled rates of shoreline erosion, further driving marsh platform loss that is likely to be permanent; and (*iv*) after 18 mo, marsh grasses have largely recovered into previously oiled, noneroded areas, and the elevated shoreline retreat rates observed at oiled sites have decreased to levels at reference marsh sites. This paper highlights that heavy oil coverage on the shorelines of Louisiana marshes, already experiencing elevated retreat because of intense human activities, induced a geomorphic feedback that amplified this erosion and thereby set limits to the recovery of otherwise resilient vegetation. It thus warns of the enhanced vulnerability of already degraded marshes to heavy oil coverage and provides a clear example of how multiple human-induced stressors can interact to hasten ecosystem decline.

geomorphology | multiple stressor | wetland | human impacts

Human activities severely threaten coastal ecosystems and the critical services they provide worldwide (1–4). Pollution from point-source release is often among the most intense of these anthropogenic stressors and can drive severe and rapid degradation of local habitats, such as seagrasses, mangroves, and coral reefs (e.g., refs. 5–8). Oil spills, in particular, pose a heightened threat to ecosystem health because they are unpredictable in space and time, and the resources needed to minimize impacts are often not immediately available (e.g., a containment cap for a well blowout) (9). Past oil spills in coastal habitats have led to immediate effects such as widespread animal die-offs and losses of ecosystem services (e.g., refs. 5, 7, 10–12) as well as longer-lasting effects, such as alteration of animal behaviors and persistence of oil-derived compounds in food webs (e.g., refs. 5–8, and 13–21).

In April 2010, well blowout on the seafloor below the BP-contracted *Deepwater Horizon* (BP-DWH) oil-drilling vessel, ~80 km off the Louisiana coast, led to the eventual release of an estimated 4,900,000 barrels of crude into Gulf of Mexico waters (22), some portion of which ultimately landed in nearby shoreline ecosystems (23). Various sources estimate that ~75 linear km of salt marsh in Louisiana experienced moderate to heavy oiling, the most of any state (24, 25) (Fig. S1). Gulf of Mexico coastal habitats are economically important, generating more than $10 billion per year in revenues through fisheries and tourism (4, 24, 26). Salt marshes, as one of the most common ecosystems in this region, are critical to maintaining these valuable ecosystem services (4, 26, 27). Past studies investigating effects of oil spills on salt marshes indicate that negative impacts on plants can be overcome by vegetation regrowth into disturbed areas once the oil has been degraded (8, 28–30). This finding suggests that marshes are intrinsically resilient to (i.e., able to recover from) oil-induced perturbation, especially in warmer climates such as the Gulf of Mexico, where oil degradation and plant growth rates may be high.

Here, we report on underappreciated indirect effects caused by the interaction between shoreline oiling and geomorphic feedbacks in salt marshes that dramatically reduce salt-marsh resilience to oil disturbance. In oil spill-impacted Louisiana marshes, we examined (*i*) the magnitude of oil contamination at different distances from the shoreline; (*ii*) the effects of this oil contamination on salt-marsh flora, fauna, and shoreline position; and (*iii*) the recovery of salt-marsh ecosystems after intense and localized oil coverage. To evaluate oil impacts on the marsh ecosystem, we used a multicomponent approach of (*i*) replicated, control-impact–paired time-series studies; (*ii*) shallow-water, oceanographic wave-propagation modeling; and (*iii*) in situ field experiments.

Results and Discussion

In October 2010, about 5 mo after initial oil contact, we surveyed marsh sites throughout Barataria Bay, LA, a coastal region that experienced some of the most extensive BP-DWH oil contamination (Fig. S1). Although interior marsh regions were intact (vegetation >15 m from the marsh edge), marsh shoreline habitats (<15 m from the marsh edge) were mixtures of apparently healthy and severely degraded, oil-impacted sites (i.e., muddy areas laden with oil-covered dead and horizontally laying, decaying grass stems). At oil-impacted sites ($n = 3$; *Methods*), we found abundant oil residues (up to 82% on an aerial basis; Figs. 1*A* and 2) on the marsh substrate, in contrast to the low levels of other known plant stressors (i.e., redox potential, soil salinities, fungal-farming snails; Figs. S2 and S3) that have driven previous marsh community die-offs (31–35). No oil residue was observed at our reference sites ($n = 3$) on either marsh plants or the substrate (Fig. 1*A*). In addition, levels of total polyaromatic hydrocarbons (PAHs; a proxy for oil residue abundance) found in the surface sediments at impacted sites was >100 times higher than concentrations found in reference marshes (Fig. 1*B*).

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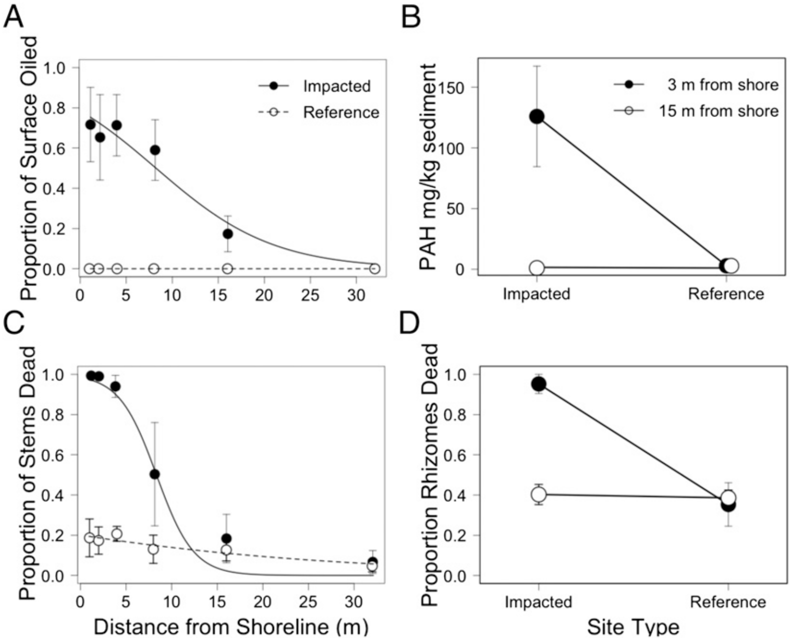

Fig. 1. Surveys of oil cover and cordgrass across transects at impacted (●) and reference (○) sites in October 2010. (*A*) Change in the proportion of plants oiled with distance from shoreline (defined as marsh platform edge). (*B*) Sediment PAH concentrations at three impacted and three reference sites at 3 m and 15 m from the shoreline. The more than 100-fold greater difference between concentrations at reference and impacted sites was not significant at inshore regions. (*C*) Change in the proportion of aboveground plants dead with distance from the marsh edge. A significantly greater proportion of the surface was oiled at impacted than at reference sites ($P < 0.001$), but oil coverage declined rapidly with distance reaching less than 50% coverage by 8.2 m from the marsh edge. There was also a greater proportion of plants dead at impacted sites (confirming our site characterizations) ($P < 0.001$). However, concomitant with the reduction in oil coverage with distance from shoreline, the proportion of dead plants at impacted sites also decreased with distance from the marsh edge, with the proportion of plants surviving exceeding 50% beyond 8.3 m from shore. Data illustrated in *A* and *C* are means from replicated surveys ($n = 5$) at three different reference and impacted sites. (*D*) Change in proportion of rhizomes dead at 3 m and 15 m distances from the shoreline at reference and impacted sites. There was a significant interaction between site type and distance from shore ($P = 0.0003$). This result is driven by the near-shore die-off zone where rhizome mortality was 63% higher at impacted than at reference sites. Data illustrated in *B* and *D* are means from three different reference and impacted sites ($n = 3$). Error bars are SEs.

Ecological Effects. Concomitant with elevated oil cover and sediment PAH concentrations at impacted sites, we observed significantly lower snail densities (although invertebrates were generally low at all sites; Fig. S3), piles of dead snails (Fig. 2*D*), empty mussel shells (Fig. 2*C*), and near complete loss of standing aboveground plant cover extending 5–10 m from the shoreline (Fig. 1*C*). Importantly, examination of the belowground plant material revealed that ~95% of rhizomes sampled in this near-shore portion of the impacted sites were also dead, whereas only 36% of rhizomes in the same near-shore portion of the shoreline

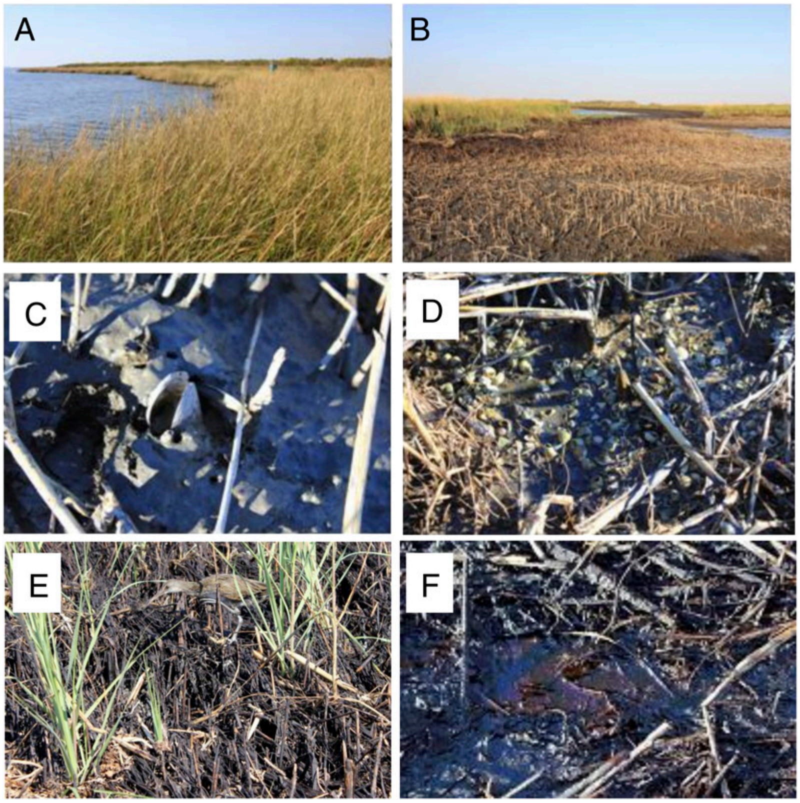

Fig. 2. Picture of (*A*) reference marsh (*B*) impacted marsh, (*C*), dead mussel at impacted site, (*D*) large pile of dead snails in impacted area, (*E*) clapper rail foraging on heavily oiled grasses at impacted site, and (*F*) typical covering of oil residue on the marsh surface at an impacted site.

in reference marshes were dead (Fig. 1*D*). Oil cover on marsh surfaces dropped precipitously at impacted sites at distances beyond 10 m from the shoreline, and live plant cover concomitantly increased to more than 50% (Fig. 1 *A* and *C*). Levels of PAHs decreased beyond 15 m from the shoreline and were not statistically different from those at reference marsh sites (Fig. 1*B*). Aboveground plant and rhizome concentrations also increased beyond 15 m to match those found in reference marshes (Fig. 1 *C* and *D*).

These data provide evidence of salt-marsh community die-off in the near-shore portion of the Louisiana shoreline after the BP-DWH oil spill because of high concentrations of oil at the edge of the marsh. Specifically, these findings suggest that the vegetation at the marsh edge, by reaching above the highest high-tide line in the microtidal environment of the Gulf of Mexico, blocked and confined incoming oil to the shoreline region of the marsh. This shoreline containment of the oil may have protected inland marsh but led to extensive mortality of marsh plants located from the marsh edge to 5–10 m inland and to sublethal plant impacts on plants 10–20 m from the shoreline, where plant oiling was less severe. This assertion is also supported by data from our field experiment and supplemental field surveys that assessed impacts of covering by oil (collected from the marsh surface) on the health of live marsh plants (Fig. 3, *Methods*, and *SI Methods*). Specifically, our studies revealed a nonlinear relationship between stem oil coverage and stem death and a threshold of oil coverage of ∼65%, beyond which plant death occurred—the same high-oil coverage observed on plants and the marsh surface at the seaward edge of our impacted marsh sites and across an additional four oiled sites we surveyed (Fig. 3). Moreover, tests of alternative causes for marsh die-offs, such as drought, inundation, or grazers, all failed to explain the observed pattern of ecosystem loss (*SI Methods*). These data also suggest that the mechanism of the lethal effects of oil are more likely derived from interference with respiration and photosynthesis (reviewed in ref. 8) than from direct toxicity because plant death only occurred at high levels of oil coverage.

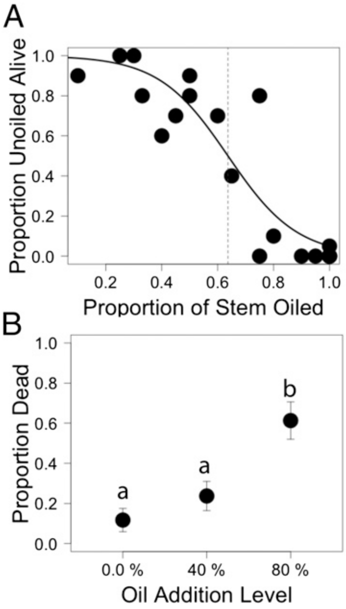

Fig. 3. Oil cover versus plant death as assessed from field observations and from manipulations. (*A*) Field observations of level of oil on individual plants and resultant plant death, indicated by blade browning. The proportion of plant stems that were green and alive is greater than the proportion dead (i.e., indicating improved health) when oil coverage dropped below 64%. (*B*) Observation of blade browning 30 d after a treatment of oil coverage of 40% or 80% of the plant's height (*n* = 6 per oil-addition treatment). Superscript letters indicate treatments that were significantly different ($P < 0.05$) based on Tukey's HSD post hoc comparison. Error bars are SEs.

Biogeomorphological Feedback. Oil concentrated on the marsh edge enhanced the rate of decline of Louisiana salt marshes, which are known to be degrading at an alarming pace (e.g., refs. 35–38). Specifically, erosion on the steep edges of these already receding marsh platforms was more than twice as high at oil-impacted sites than at reference sites during the period between October 2010 (∼5 mo after oil was reported on Louisiana marshes) and October 2011 (Fig. 4*A*). After October 2011, erosion rates did not differ between impacted and reference sites (Fig. 4*A*). In nondegraded salt-marsh plant communities, belowground plant architecture is characterized by a complex network of underground roots and rhizomes generated by clonally reproducing plants (39–41). This elaborate root matrix helps to maintain shoreline structure and retard erosion by binding sediments and increasing concentrations of organic matter that act as adhesive agents (38, 42–45). Our results suggest that oil-generated death of this stabilizing root matrix at the edges of these marshes triggered a geomorphic response that led to accelerated erosion of the marsh edge, hastening the degradation of the elevated platform on which marsh vegetation depends (35, 46–50) (Fig. 4). Our study sites were all of similar physiographic character because there were no differences in the shallow-water slopes among reference and impacted sites ($P = 0.55$). We conducted numerical simulations of wind-generated wave growth and propagation with SWAN (51) to ensure that differences in observed erosion rates between impacted and reference sites were not attributable to a predisposition of the impacted sites to higher erosion rates (Fig. S4). In fact, the model results demonstrate that our reference sites receive slightly higher wave-energy fluxes than the impacted sites (Fig. S4).

Ecosystem Resilience and Degradation. Despite the deleterious effects of the oil spill on marsh vegetation and erosion rates, we found clear evidence for recovery processes. In our transect surveys at impacted sites in April 2011 (∼11 mo after oil coverage occurred on these marshes), we documented significant increases in plant cover (up to 33%, on average ∼20%; Fig. 4 *C*–*F*) in areas that were barren and had nearly complete die-back of roots during our initial surveys (Figs. 1*C* and 2). Because we observed no seedling establishment in impacted areas, this recovery likely occurred via plant lateral regrowth (i.e., clonal growth) originating from interior marsh areas where plants were less affected or from nearby, small remnant patches in the impacted areas (52). This clonal regrowth of marsh plants continued throughout the summer of 2011, with full recovery of the marsh plant cover occurring sometime between October 2011 and January 2012, ∼1.5 y after the oil spill (Fig. 4). As predicted from past studies (36, 42–45), plant shoreline reestablishment suppressed the observed accelerated erosion rates at impacted sites to values not significantly different from those at reference sites (Fig. 4 and Fig. S4). However, no plant recovery was observed in the marsh platforms lost to accelerated erosion, and marsh plants that were transplanted into these eroded areas in June 2011 died within 2 mo (Fig. S5 and *SI Methods*), whereas those planted in nonoiled areas of both reference and impacted sites remained alive as of January 2012. Our observations agree with past modeling studies revealing that accelerated erosion on marsh cliffs in Louisiana reduces substrate surface to subtidal elevations and thereby prohibits the recovery of salt-marsh vegetation (48, 53, 54). However, our observations are in contrast to a number of previous studies from other regions that found, under natural conditions, salt-marsh vegetation is resilient to this stress and reestablishes seaward of eroding edges (33, 48, 55). The absence of recovery of marsh vegetation seaward of the

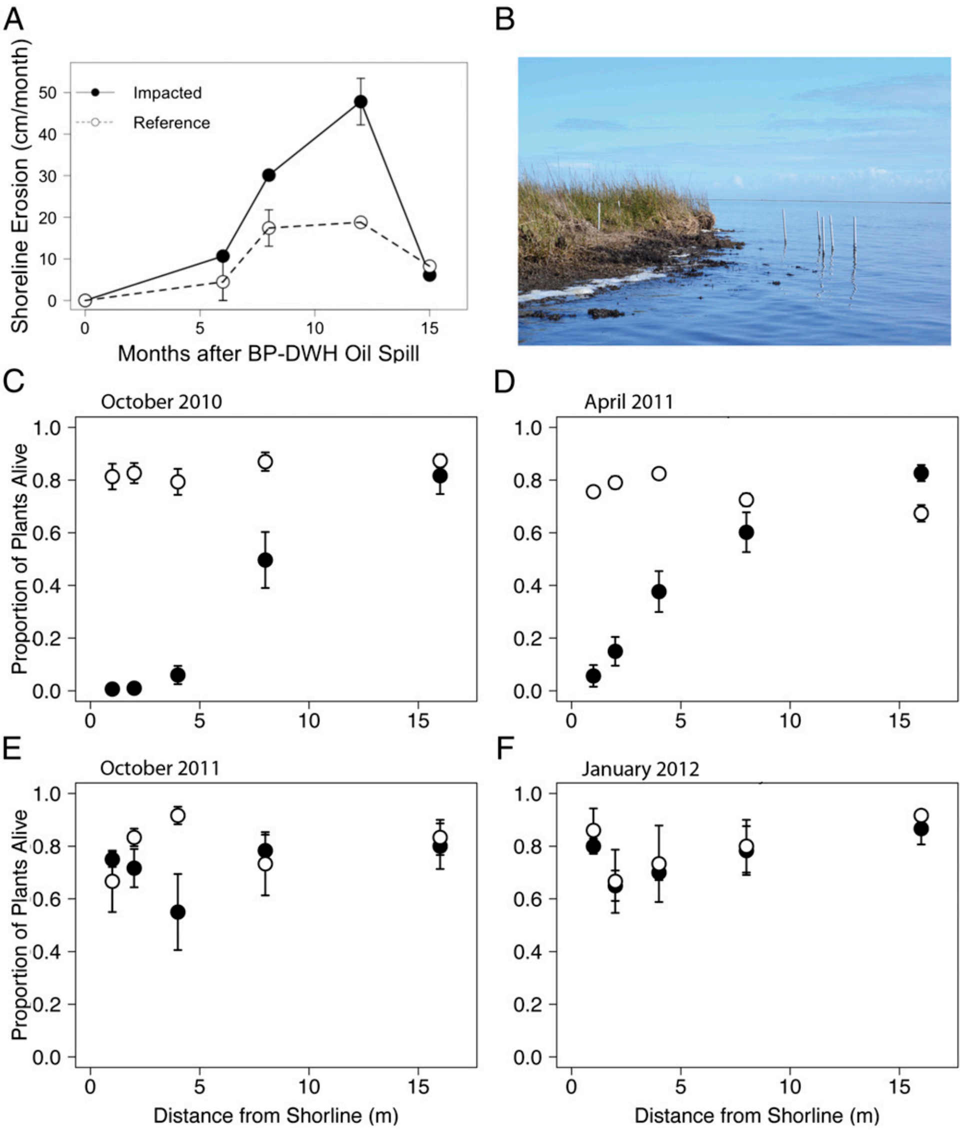

Fig. 4. (*A*) There was a significant increase in average lateral shoreline erosion rate between reference and impacted sites ($P = 0.007$) based on measurements at each site type. Error bars are SEs, and unseen error bars are smaller than symbols. (*B*) Photo of erosion monitoring poles at an impacted site. Right-most PVC poles were installed to mark the marsh platform edge, and retreat of the marsh from this initial starting point is apparent. (*C–F*) Comparison between average percentage of plants alive at four times at impacted and reference sites from 0 to 15 m from the shoreline ($n = 3$). There was a significant effect of the presence of oil, the distance from shoreline, and time ($P < 0.0001$), with much lower plant coverage near shore for impacted sites than for reference sites during October 2010 and April 2011 but with similar levels of coverage near shore during October 2011 and January 2012 at these sites. Plant coverage was similar for all sites and times at greater distances from the shoreline beyond 10 m from the marsh edge.

retreating marsh cliffs in Barataria Bay underscores that this oil spill has decreased the resilience of these marshes by triggering accelerated substrate erosion, which, in turn, reduces the overall area that can be recolonized by plants (Fig. S5).

Our results suggest that there are reasons for both optimism and concern about the impact of this oil spill on Mississippi deltaic marshes of Louisiana. On one hand, our results reveal that marsh vegetation displays remarkable resilience to oil spills by concentrating and confining the effects of oil to the marsh edge, recovering fully in noneroded areas after ∼1.5 y, and suppressing, through this recolonization, further accelerated erosion rates along the shoreline. The lack of oil on the marsh surface or on grasses at distances greater than 15 m from the shoreline at any site (Fig. 1*A*) suggests that incoming oil sheens were contained and prevented from moving into interior marshes by a baffling wall of live and dying salt-marsh grasses, a process that in itself increases the resistance of the extensive marsh ecosystem to oil spill. However, this resistance comes at a high cost for the impacted areas because marsh grass die-off and subsequent sediment exposure to waves resulted in a more than doubling of the rate of erosion of the intertidal platform, leading to permanent marsh ecosystem loss (Fig. 4). Specifically, we observed an average rate of marsh shoreline retreat of ∼1.38 $m \cdot y^{-1}$ (Fig. 4*A*) at our reference sites, a level consistent with that reported in other studies for this area of Louisiana (0.8–1.3 $m \cdot y^{-1}$) (38). This already high rate of shoreline retreat increased by more than 125% to ∼3.0 $m \cdot y^{-1}$ at oil-impacted sites. Indeed, the extent of habitat loss could have been even more severe if a large storm or hurricane had coincided with the period of increased shoreline exposure after oil-driven die-off. In fact, the rapid shoreline retreat rates observed between April and October 2011 may be attributable to the effects of Hurricane Lee in September

2011, which made landfall immediately west of Barataria Bay, bringing high winds and surge-related flooding to the region. The highly elevated erosion rates after oil-driven marsh grass die-off observed in this study (Barataria Bay and Bay Jimmy; Fig. S1) are likely general and can be extrapolated to the other marshes in Louisiana that also experienced moderate-to-heavy oil coverage because these marshes are also typically characterized by erosive edges (33, 55–57).

More broadly, our results reveal that multiple stressors are interacting in Louisiana marshes to hasten ecosystem decline. Louisiana experiences some of the highest rates of salt-marsh loss in North America (~75 km^2/y) as a result of natural subsidence and channelization of the Mississippi River, which reduces sediment supply to the coast, causing submersion of the marsh interiors and formation of erosion-prone, cliffed edges (31, 37, 54). Our observations and experimental work demonstrate that intense oil coverage of these already degraded marsh edges interacts with preexisting sediment-limitation stress to amplify permanent habitat loss along the marsh margins. The edges of healthy marshes are typically characterized by more gently sloping banks and therefore tend to be more resistant to erosion than subsiding, deltaic-plain marshes in Louisiana that are often characterized by erosive cliff edges (33, 55–57). This study highlights the enhanced vulnerability of these already degraded marshes to heavy oil coverage associated with oil spills and provides a clear example of how multiple human-induced stressors can interact to hasten the loss of a critical marine ecosystem and the services it provides.

Although the amount of increased erosion caused by loss of marsh plants from oiling is, in many ways, specific to these oil-impacted areas in Louisiana (e.g., because of the microtidal environment and long-term sediment deprivation from river channelization), the mechanisms underlying these results can likely be extended to other oil-impacted coastal salt marshes that are also characterized by erosive edges or cliffs. In fact, erosion of marshes in response to oil coverage has been observed or suggested in studies in New England, Florida, and Louisiana (58–62). Our study goes one step further to show that direct vegetation die-off is the primary result of heavy oil coverage, but that erosion caused by biogeomorphological feedback and subsequent habitat loss may ultimately determine the long-term effect of oil pollution in salt marshes. Future research should focus on how the interplay between biological and geomorphological processes affects the vulnerability of salt marshes facing multiple anthropogenic stressors.

Methods

All work was conducted in *Spartina alterniflora* (cordgrass)-dominated salt marshes in Barataria Bay, LA, one of the heaviest-impacted areas after the BP-DWH oil spill (Fig. S1). Sites were identified as either "impacted" or "reference." Impacted sites had substrate that were denuded and/or laden with dead and decaying cordgrass stems. Reference sites were dominated by standing live cordgrass plants. All impacted sites were located in the northeast corner of Barataria Bay, near Bay Jimmy, which received large amounts of oil coverage because of prevailing winds and currents after the BP-DWH oil spill (Table S1). Two reference sites were selected in the northwest corner of the bay, east of Hackberry Bay, and an additional reference site was located in Grand Isle State Park on the south side of the bay. All sites were located within 30 km of each other. All but the Grand Isle State Park site faced outward into the same portion of open Barataria Bay, thus experiencing similar tidal fluctuations and weather conditions. Because the Grand Isle site was relatively protected from wave action, this site was not included in our comparison of erosion rates between reference and impacted sites (see Table S1 for coordinates of reference and impacted sites). At both reference and impacted sites, we ran an oil-addition and a marsh plant transplant experiment, and we conducted surveys in which oil coverage, PAH concentrations, live plant (*S. alterniflora*) coverage and survival, invertebrate abundances, pH, redox and salinity, as well as erosion potential and erosion rates were quantified (for detailed sampling and analytical methods, see *SI Methods*).

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