Accelerated marsh loss in Louisiana following the *Deepwater Horizon* oil spill

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Abstract:

Following the *Deepwater Horizon* (DWH) oil spill, comparative field studies from a limited number of sites demonstrated that heavy oiling of salt marsh shorelines led to plant death and increased marsh erosion along already escarped edges. Using data collected as part of the natural resource damage assessment, we explored the generality of this effect by examining the relationship between the degree of plant stem oiling and shoreline erosion rates for mainland herbaceous salt marshes in coastal Louisiana. Data collected between fall 2010 and spring 2013 at 77 salt marsh sites revealed a threshold relationship between the degree of plant stem oiling and marsh erosion rate. Significantly higher erosion rates occurred at marsh sites with the highest amount of plant stem oiling and this impact was coincident with significant loss of above-ground biomass at those sites. Elevated erosion rates at heavily oiled sites occurred for ~1–2 years after the spill, and then returned to levels statistically indistinguishable from rates at unoiled sites. This analysis documents permanent land loss as a result of the DWH spill.

Introduction

In the summer of 2010, oil released from the Deepwater Horizon (DWH) disaster coated salt marshes along more than a thousand kilometers of shoreline across the Gulf of Mexico (Michel et al. 2013). Because the marshes in the affected areas of the Gulf are microtidal, the oil that reached these marshes was most heavily concentrated along the marsh edge. While the extent of oiling into the marsh from the shoreline varied widely across affected marsh habitats, the heaviest oiling was generally concentrated along a black belt < 15 meters in width (e.g., Silliman et al. 2012). Marsh oiling from the DWH spill thus created a concentrated disturbance on the ecosystem's already stressed edge. Comparative field studies at a limited number of sites indicated that heavy oiling led to elevated lateral erosion rates, most likely because it killed both plant stems and roots, resulting in decreased soil strength and reduced resistance to wave erosion (e.g., Mendelssohn et al. 2012; Silliman et al. 2012; McClenachan et al. 2013). Most of the shoreline oiling in marshes, however, was characterized as light to intermediate, and little is known about the impact of oiling on marsh erosion across a range of oiling levels.

This study uses data collected as part of the natural resource damage assessment process. The dataset used here was collected for the Coastal Wetland Vegetation (CWV) survey (Hester and Willis 2011), and includes data from mainland herbaceous marshes, collected across 77 sites spanning 5 categories of oiling defined by the percentage of stem height oiled (0%, 0–10%, 10–50%, 50–90% or 90–100%) (Hester and Willis 2011). At each site, cumulative erosion was monitored based on field surveys of marsh retreat relative to a datum established in the fall of 2010. We used these data to examine the relationship between plant stem oiling and marsh erosion rates, and to test for thresholds in the functional relationship between oil stress and erosion rates. As previous field experiments have shown that (1) death of belowground plant biomass is associated with accelerated erosion rates (Silliman et al. 2012; Silliman et al. *in review*), and (2) death of both aboveground (Hester et al, 2015) and belowground biomass (Silliman et al. 2012) are pronounced at the heaviest oiling levels, our hypotheses were that erosion rates would be positively correlated with oiling, and that this response might exhibit threshold behavior at the highest (90-100%) stem oiling levels.

Methods

Field methods

The CWV survey included multiple types of marsh. Here, we analyzed erosion data only from mainland herbaceous marshes, as our previous experimental and comparative studies were also conducted in mainland herbaceous marshes (Silliman et al. 2012; Silliman et al. *in review*). Mainland herbaceous marshes sampled during the CWV study are located primarily along the inland edges of protected bays and estuaries, and are dominated by *Spartina alterniflora*, (e.g., Hester et al., 2015). The initial CWV survey of Louisiana marsh sites was conducted based on a stratified random sample of 78 sites from a collection of 713 marsh pre-assessment survey sites (e.g., Hester et al., 2015). Strata were defined by the extent of stem oiling observed during the pre-assessment survey (0%, 0–10%, 10–50%, 50–90%, and 90–100%), which occurred between late May and early September of 2010 (Hester et al. 2015). Measurements of marsh edge position were made in fall 2010, spring 2011, fall 2011, fall 2012, and fall 2013. One of the 78 CWV sites was missing data in fall 2012 and fall 2013; the final dataset described here therefore includes 77 of the 78 CWV sites.

At each site, survey teams established marsh edge and inland stakes using polyvinyl chloride (PVC) poles to demarcate the beginning and end of a line transect perpendicular to the

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shoreline. The shoreline stake was placed at the marsh edge and the inland stake was placed at the furthest inland point of oiling documented either during the pre-assessment or transect installation. Transects ranged from 3 m to 30 m in length. On each sampling date, survey teams measured the length from the inland stake to the current marsh edge. Complete details on the CWV survey design and field observations can be found in Hester and Willis (2011).

To account for effects of incident wave energy on erosion rates, we used a measure of relative wind-wave exposure that was quantified for each of the sites (Keddy 1982; Nixon, 2015). This metric, referred to as the mean wave exposure index, is calculated from the product of average wind speed and fetch along each of 8 cardinal directions. A detailed description of how the wave exposure index was calculated can be found in Nixon (2015).

Data analysis

Differences in marsh erosion rates among stem oiling categories were evaluated using a Kruskal-Wallis test, a linear rank test, and an analysis of means. The Kruskal-Wallis test evaluates any difference between stem oiling levels, whereas the linear rank test is best at detecting monotonic or step changes, and the analysis of means detects whether one group differs from the others. All three of these tests are non-parametric procedures because the data did not meet the normality or equal variances assumptions of analysis of variance (ANOVA). The Kruskal-Wallis statistic is $\sum n_i \ (R_i - \bar{R})^2$, where R_i and n_i are the average rank and sample size for each stem oiling group, respectively. The linear rank statistic is $\sum i \ R_i$ (Hollander et al. 2014). The analysis of means (Nelson et al. 2005) compares the erosion rate for each stem oiling level to the overall erosion rate in all sites. The nonparametric version of analysis of means (Bakir 1994) is based on ranks for each stem oiling group. The null distribution of each statistic was evaluated by randomization, using 9999 randomizations of stem oiling values to erosion values. Differences were considered significant at the level $P < 0.05$. No adjustment for multiple testing was made because of the *a-priori* expectation that the differences would be largest in the 90–100% stem oiling group.

To address the influence of variation in wave exposure among marsh sites, we repeated these analyses after grouping observations by similar wave energy. This approach is an extension of the Skillings-Mack method (Skillings and Mack 1981). Breakpoints between wave energy groups were set at the deciles of mean wave energy, giving 10 groups. Measured erosion rates were then ranked within each wave energy group. We computed the mean and median erosion in each stem oiling group and compared those values to distributions obtained by randomly reassigning erosion values to stem oiling groups within each wave energy group. Mean excess erosion for each stem oiling group was computed as the difference between the mean observed erosion and the mean of the randomly reassigned erosion values. P-values and 95% confidence intervals for excess erosion were obtained by randomly permuting erosion values within each wave-energy block using 9999 randomizations. We repeated the analysis using 5 and 15 groups of wave energy. Our results were insensitive to the number of wave energy groups, so we present here only the results from analyses using 10 wave energy groups.

Results

The mean cumulative (2010–2013) erosion in the 90-100% stem oiling group was 4.0 m/yr, compared to mean erosion rates of 1.4 to 2.1 m/yr in the other four stem oiling groups (Figure 2A; Table S1A). The linear rank test shows evidence of a monotonic or step change ($p = 0.002$), while the Kruskal-Wallis test indicates at least one difference ($p = 0.033$). Based on analysis of means, the total unadjusted erosion from 2010 to 2013 was significantly higher for the 90–100% oiling category relative to the other categories (Figure 2A and Table S1A; $p = 0.011$).

After adjustment for wave energy, the erosion rate in the 90-100% stem oiling group was 1.6 m/yr more than expected ($p = 0.13$), while the mean erosion rates in the other four stem oiling groups varied from 0.1 m/yr more than expected to 0.8 m/yr less than expected (Figure 2B). However, due to substantial within-group variation and a relatively small sample size, neither of the overall statistical tests detected a statistically significant difference (Figure 2B and Table S1B; Kruskal-Wallis, $p = 0.18$, and linear rank $p = 0.47$).

On a year-by-year basis, mean wave-adjusted erosion rates were 1.6 m/yr higher than expected in the 90–100% stem oiling category from fall 2010–fall 2011 (Figure 3 and Table S2; $p = 0.040$). For fall 2011–fall 2012, wave-adjusted erosion was 3.0 m/yr higher than expected for the highest stem oiling category, but this difference was not statistically significant ($p = 0.068$). By the third year of the study (fall 2012–fall 2013), erosion rates for the highest oiling category were no longer elevated relative to the other categories.

Total erosion values for some of the sites in the data frame could be considered "outliers," using the criterion of being more than three standard deviations from the mean erosion within a stem oiling group. Using this criterion, three sites had 2010-2013 erosion rates that were unusually large, relative to other values in the same stem oiling group. There was one "outlier" in each of the 0-0%, 0-10%, and 10-50% oiling groups. Removing these sites from the analysis did not substantially change the conclusions.

Discussion

Previously published comparative field studies indicate that heavy stem oiling from the DWH spill led to the death of vegetation along the marsh edge (Lin and Mendelssohn 2012; Silliman et al. 2012; McClanahan et al. 2013; Hester et al. 2015) and increased erosion rates (Silliman et al. 2012; McClanahan et al. 2013). Oiling in these previous studies was described in terms of soil PAH concentrations or qualitative observations of shoreline oiling. Our analysis of the Louisiana CWV survey results indicates that (1) the erosion effects of plant stem oiling revealed in these small-scale observational studies also occurred in the larger area of impacted coastal salt marshes, and (2) there is a threshold at which there are statistically detectable effects of plant stem oiling on marsh edge erosion rates.

Specifically, our results provide evidence that oiling accelerated erosion rates only at the highest plant stem oiling levels. We observe this effect in the first two years following the spill, even when erosion rates are normalized to correct for the effects of wave exposure on marsh edge erosion. These results suggest that the oil disturbance-erosion functional relationship in salt marshes exhibits threshold behavior, with no observable difference in erosion rates relative to unoiled marsh at the lowest stem oiling levels followed by an increase in erosion rates at the highest stem oil levels.

We hypothesize that the mechanism leading to oil-triggered increases in erosion rates was the death of belowground plant material at these high stem oiling levels, and an associated reduction in soil strength due to loss of cohesive plant roots. Previous studies have documented that belowground marsh plant material experiences significant die-back as a result of heavy oiling, as measured by soil PAH concentrations (Lin et al., 2002; Judy et al., 2014), qualitative observations such as SCAT categories (McClanahan et al., 2013), or plant stem oiling (e.g., Judy et al., 2014; Silliman et al. 2012; Hester et al. 2015). Furthermore, small-scale experimental studies demonstrate that edge erosion rates increase if there is a loss of belowground marsh plant material (Silliman et al. *in review*). Although live belowground biomass and soil strength were not measured as part of the CWV study, comparative and experimental studies examining oil impacts on *Spartina alterniflora* marshes demonstrate that exposure to heavy oiling for extended time periods, especially oiling of the soil, kills belowground plant material in these marshes (Michel et al. 2009; Silliman et al. 2012; McClenachan et al. 2013). Survey results from the same sites where we observed accelerated erosion rates also demonstrate that there was a significant, negative effect of heavy oiling on aboveground biomass of salt marsh plants, and that this effect was most pronounced at the highest stem oiling levels for the first two years after the spill (Hester et al. 2015). Thus, it is very likely that belowground plant material was also lost at the heavily oiled sites where we observed accelerated erosion after the DWH spill.

These results, combined with experimental and comparative studies, provide evidence that elevated marsh-edge erosion at sites with the highest amount of plant stem oiling was a spatially extensive effect that resulted from the DWH spill. Since past experimental transplant studies into these eroded areas along marsh edges demonstrate that marsh plants cannot regrow due to inundation stress (Silliman et al. 2012), it can be concluded that these erosional losses led to permanent land loss along affected marsh edges of the Gulf of Mexico.

The increased erosion rates in the highest stem oiling group were no longer detected ~18 months after the DWH spill. This observation is consistent with results from a more process-oriented, but smaller scale study of the impacts of heavy oiling on shoreline erosion rates following the DWH disaster (e.g., Silliman et al. 2012). It is also consistent with plant health observations reported by Hester et al. (2015) where the majority of significant reductions to plant health and productivity due to plant oiling occurred through 2012.

The increased erosion rates documented in this study are associated with the death of heavily oiled vegetation. Other studies conducted as part of the natural resource damage assessment demonstrate that accelerated erosion was also correlated with death of intertidal oysters (Powers et al., 2015) and with response activities on heavily oiled marshes (Gibeaut et al. 2015). Permanent land loss is therefore likely to have occurred in a variety of environments, from a variety of mechanisms, as a result of the DWH oil spill.

Literature Cited

Andren, H., and P. Angelstam. 1988. Elevated predation rates as an edge effect in habitat islands: experimental evidence. Ecology 69:544–547.

Angelini, C., and B. R. Silliman 2012. Patch size-dependent community recovery after massive disturbance. Ecology 93:101–110.

Bakir, S. T. 1994. Analysis of means using ranks for the randomized complete block design. Communications in Statistics – Simulation and Computation 23:547–568.

Côté, I. M., and E.S. Darling. 2010. Rethinking ecosystem resilience in the face of climate change. PLoS Biology 8:e1000438.

Couvillion, B. R., J. A. Barras, G. D. Steyer, W. Sleavin William, M. Fisher, H. Beck, N. Trahan, B. Griffin, and D. Heckman. 2011. Land Area Change in Coastal Louisiana from 1932 to 2010: U.S. Geological Survey Scientific Investigations Map 3164, scale 1:265,000, 12 p. Pamphlet. http://pubs.usgs.gov/sim/3164/downloads/SIM3164_Pamphlet.pdf.

Dale, V. H., L. A. Joyce, S. McNulty, R. P. Neilson, M. P. Ayres, M. D. Flannigan, P. J. Hanson, L. C. Irland, A. E. Lugo, C. J. Peterson, D. Simberloff, F. J. Swanson, B. J. Stocks, and B. M. Wotton. 2001. Climate change and forest disturbances. Bioscience 51:723–734.

Day, J. W., D. F. Boesch, E. J. Clairain, G. P. Kemp, S. B. Laska, W. J. Mitsch, H. Mashriqui, D. J. Reed, L. Shabman, C. A. Simenstad, B. J. Streever, R. R. Twilley, C. C. Watson, J. T. Wells, and D. F. Whigham. 2007. Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. Science 315:1679–1684.

Dodds, W. K., W. H. Clements, K. Gido, R. H. Hilderbrand, and R. S. King. 2010. Thresholds, breakpoints, and nonlinearity in aquatic ecosystems as related to management. Journal of the North American Benthological Society 29:988–997.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. Annual Review of Ecology, Evolution, and Systematics 35:557–581.

Gibeaut et al., 2015. Relationship between shoreline oiling/treatment and erosion. DWH NRDA Shoreline Technical Working Group Report. Prepared for National Oceanic and Atmospheric Administration.

Hester, M. W., and I. A. Mendelssohn. 2000. Long-term recovery of a Louisiana brackish marsh plant community from oil-spill impact: vegetation response and mitigating effects of marsh surface elevation. Marine Environmental Research 49:233–254.

Hester, M. W.; Willis J. M. 2011. *Sampling and Monitoring Plan for the Assessment of MC252 Oil Impacts to Coastal Wetland Vegetation in the Gulf of Mexico, August 4, 2011*. Prepared for National Oceanic and Atmospheric Administration.

Hester, M. W., J. M. Willis, S. Rouhani, M. Steinhoff, and M. Baker. 2015. Impacts of the *Deepwater Horizon* Oil Spill on the salt marsh vegetation of Louisiana. DWH NRDA Shoreline Technical Working Group Report. Prepared for National Oceanic and Atmospheric Administration.

Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A. Dubi, M. E. Hatziolos. 2007. Coral reefs under rapid climate change and ocean acidification. Science 318:1737–1742.

Hollander, M., D. A. Wolfe, and E. Chicken. 2014. *Nonparametric Statistical Methods, 3rd edition.* New York: Wiley.

Judy, C. R., S. A. Graham, Q. Lin, A. Hou, and I. A. Mendelssohn. 2014. Impacts of Macondo oil from Deepwater Horizon spill on the growth response of the common reed *Phragmites australis*: A mesocosm study. Marine Pollution Bulletin 79:69–76.

Keddy, P. A. 1982. Quantifying within-lake gradients of wave energy: interrelationships of wave energy, substrate particle size and shoreline plants in Axe Lake, Ontario. Aquatic Botany 14:41–58.

Kolker, A. S., M. A. Allison, and S. Hameed. 2011. An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. Geophysical Research Letters 38:L21404.

Laurance, W. F., and E. Yensen. 1991. Predicting the impacts of edge effects in fragmented habitats. Biological Conservation 55:77–92.

Lin, Q., and I.A. Mendelssohn. 2012. Impacts and Recovery of the Deepwater Horizon Oil Spill on Vegetation Structure and Function of Coastal Salt Marshes in the Northern Gulf of Mexico. Environmental Science and Technology 46:3737-3743.

Lin, Q., I. A. Mendelssohn, M. T. Suidan, K. Lee, and A. D. Venosa. 2002. The dose-response relationship between No. 2 fuel oil and the growth of the salt marsh grass, *Spartina alterniflora*. Marine Pollution Bulletin 44:897–902.

McClenachan, G., R. E. Turner, and A. W. Tweel. 2013. Effects of oil on the rate and trajectory of Louisiana marsh shoreline erosion. Environmental Research Letters 8:044030.

Mendelssohn, I. A., G. L. Andersen, D. M. Baltz, R. H. Caffey, K. R. Carman, J. W. Fleeger, S. B. Joye, Q. Lin, E. Maltby, E. B. Overton, and L. P. Rozas. 2012. Oil impacts on coastal wetlands: implications for the Mississippi River Delta ecosystem after the Deepwater Horizon oil spill. BioScience 62:562–574.

Michel, J., Z. Nixon, J. Dahlin, D. Betenbaugh, M. White, D. Burton, and S. Turley. 2009. Recovery of interior brackish marshes seven years after the chalk point oil spill. Marine Pollution Bulletin 58:995−1006.

Michel, J., E. H. Owens, S. Zengel, A. Graham, Z. Nixon, T. Allard, and E. Taylor. 2013. Extent and degree of shoreline oiling: Deepwater Horizon oil spill, Gulf of Mexico, USA. PLoS ONE 8:e65087.

Nelson, P. R., P. S. Wludyka, and K. A. F. Copeland. 2005. *The Analysis of Means: A graphical method for comparing means, rates, and proportions*. SIAM, Philadelphia PA.

Nixon, Z., 2015. Wave Exposure Indices and Deepwater Horizon Shoreline Oling. DWH NRDA Shoreline Technical Working Group Report. Prepared for National Oceanic and Atmospheric Administration by RPI.

Peyronnin, N., M. Green, C. P. Richards, A. Owens, D. Reed, J. Chamberlain, D. G. Groves, W. K. Rhinehart, and K. Belhadjali. 2013. Louisiana's 2012 coastal master plan: overview of a science-based and publicly informed decision-making process. Journal of Coastal Research 67:S1–S15.

Powers, S.P., S. Rouhani, M.C. Baker, H. Roman, J. Grabowski, J.M. Willis, and M.W. Hester, in review. Loss of oysters as a result of the *Deepwater Horizon* Oil Spill degrades nearshore ecosystems and disrupts facilitation between oysters and marshes. DWH NRDA Shoreline Technical Working Group Report. Prepared for National Oceanic and Atmospheric Administration.

Silliman, B.R., J. van de Koppel, M. D. Bertness, L. E. Stanton, I. A. Mendelssohn. 2005. Drought, snails, and large-scale die-off of southern US salt marshes. Science 310:1803-1806.

Silliman, B. R., J. van de Koppel, M. W. McCoy, J. Diller, G. N. Kasozi, Kamala Earl, P. N. Adams, and A. R. Zimmermand. 2012. Degradation and resilience in Louisiana salt marshes after the BP – Deepwater Horizon oil spill. Proceedings of the National Academy of Sciences USA 109:11234–11239.

Silliman, B. R., M. W. McCoy, C. Angelini, R. D. Holt, J. N. Griffin, and J. van de Koppel. 2013. Consumer fronts, global change, and runaway collapse in ecosystems. Annual Review of Ecology, Evolution, and Systematics 44:503–538.

Silliman, B. R., Q. He, C. Angelini, M. L. Kirwan, J. Butler, J. C. Nifong, J. van de Koppel. *In review*. Wetland vegetation as a crucial element of suppressing coastal erosion.

Skillings, J. H., and G. A. Mack. 1981. On the use of a Friedman-type statistic in balanced and un-balanced block-designs. Technometrics 23:171–177.

Turner, R. E., and M. E. Boyer. 1997. Mississippi river diversions, coastal wetland restoration/creation and an economy of scale. Ecological Engineering 8:117–128.

Wilson, S. K., N. A. J. Graham, M. S. Pratchett, G. P. Jones, and N. V. C. Polunin. 2006. Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? Global Change Biology 12:2220–2234.

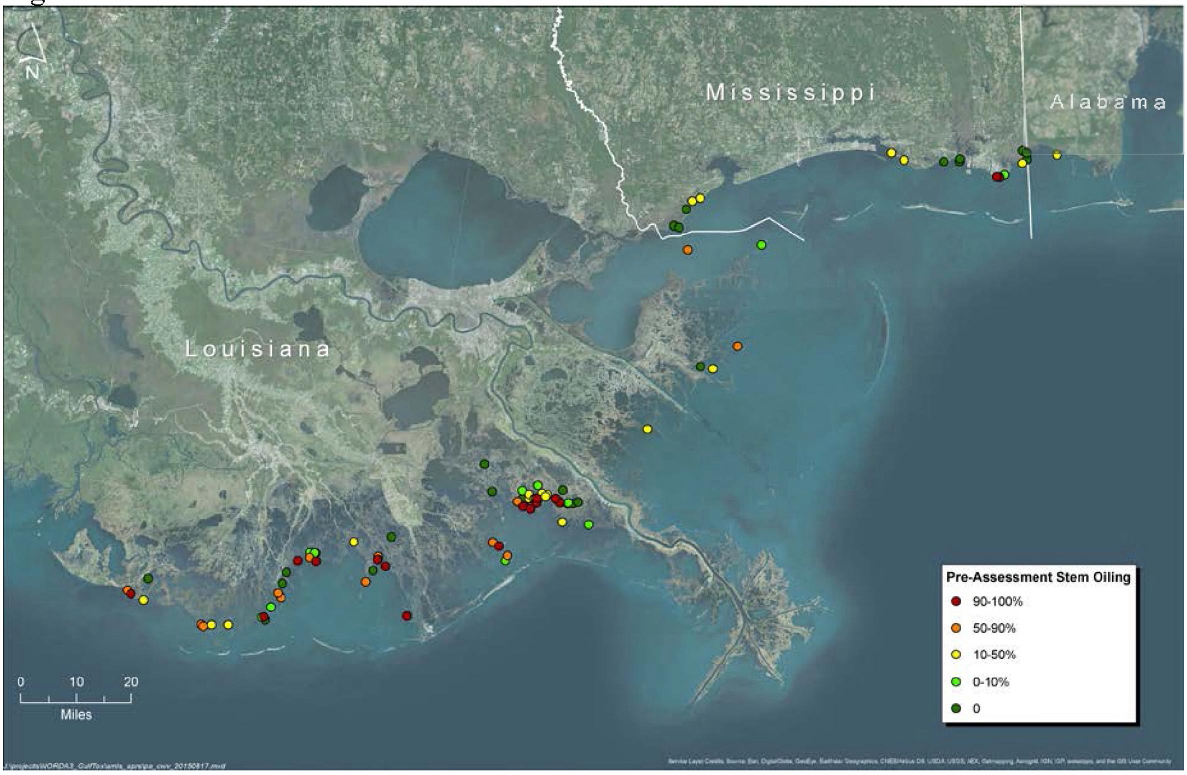
Figure Legends

Figure 1. Map of all CWV survey sites.

Figure 2. A) Box plots of *unadjusted* erosion rates (m/yr) in each stem oiling category for all Louisiana CWV sites. B) Mean excess erosion (m/yr) for each stem oiling category. Excess erosion is the difference between the observed mean erosion for that stem oiling category and the expected mean *wave-adjusted* erosion rate if there were no differences in erosion among the stem oiling categories. The vertical lines are the central 95% randomization distributions for excess erosion in each stem oiling category. When the vertical line does not cross 0, the p-value for the comparison of that stem oiling category to the overall erosion rate is less than 0.05.

Figure 3. Mean excess erosion (m/yr) by stem oiling category in 2010-2011, 2011–2012 and 2012–2013 for all Louisiana CWV sites. Symbols as in Figure 2.

Figure 1.



N
Mississippi
Alabama
Louisiana
Pre-Assessment Stem Oiling
90-100%
50-90%
10-50%
0-10%
0
0 10 20
Miles

Figure 2.

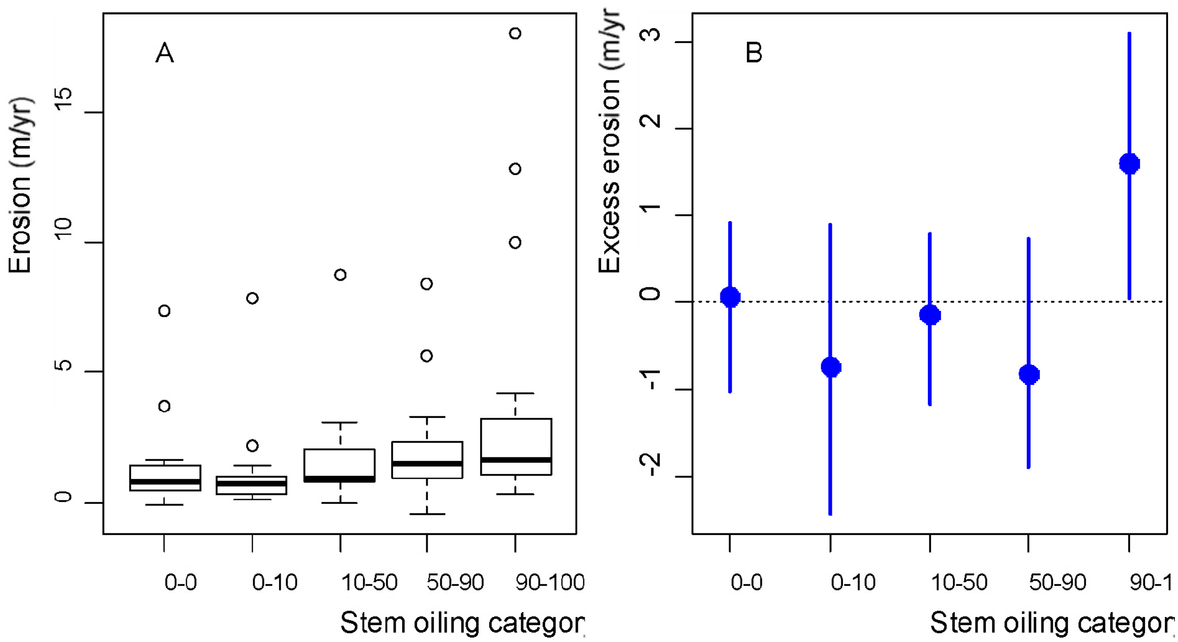


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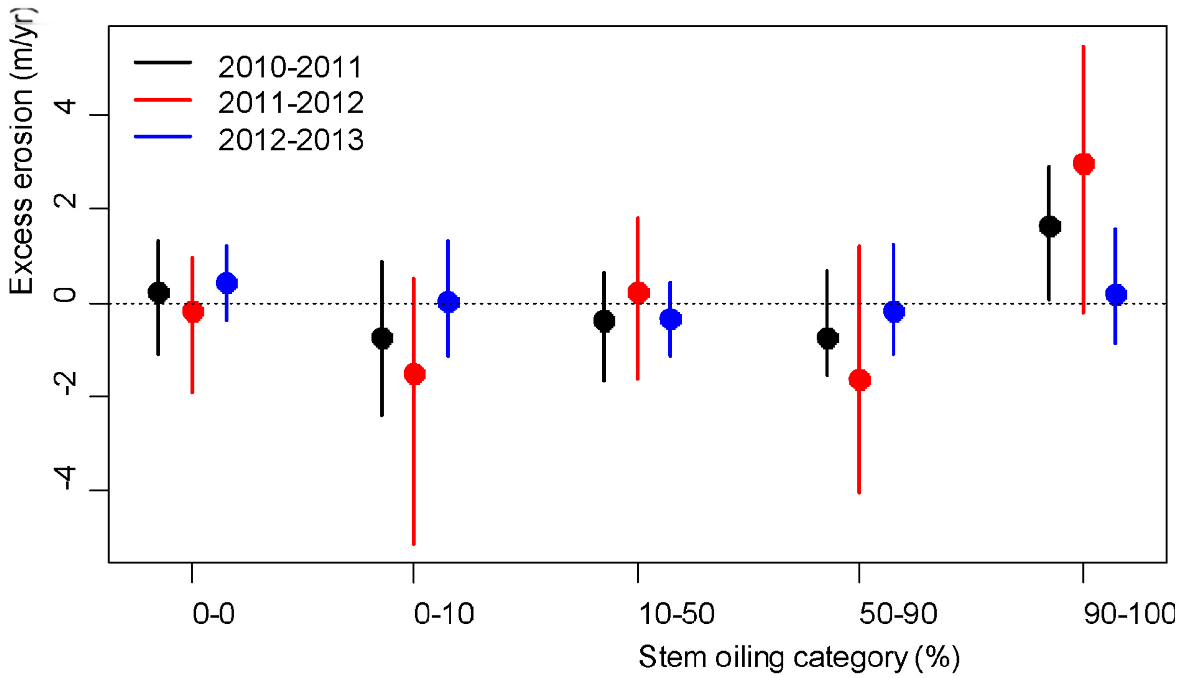
Figure 3.



2010-2011
2011-2012
2012-2013
Excess erosion (m/yr)
4
2
0
-2
-4
0-0
0-10
10-50
50-90
90-100
Stem oiling category (%)

Supplementary Information

Tables

Table S1A Summary data for Figure 2A: total mean erosion (2010–2013) in Louisiana CWV sites.

Stem oiling category	*n*	Erosion rates (m/yr)			*P*-value
		Mean	SE	Median	
0%	15	1.4	0.5	0.8	0.10
0–10%	13	1.3	0.6	0.7	0.016
10–50%	18	1.6	0.5	0.9	0.44
50–90%	16	2.1	0.6	1.5	0.12
90–100%	15	4.0	1.4	1.6	0.011
All sites	77	2.1			

Table S1B Summary data for Figure 2B, after adjusting erosion rates for wave exposure. The "expected mean, no effect of oil" represents the expected mean erosion rates when stem oiling categories are randomly assigned to sites within each wave exposure group. The "change from random expectation" values are the difference between the observed mean erosion rate and the expected mean erosion rate. The *P*-value is for the nonparametric analysis of means, comparing the median erosion rate for each stem oiling group to the overall median erosion rate, after adjusting for wave exposure.

Stem oiling category	*n*	Erosion rates (m/yr)			*P*-value
		Mean erosion rate	Expected mean, no effect of oil	Change from random expectation	
0%	15	1.4	1.4	0.1	0.14
0–10%	13	1.3	2.0	-0.7	0.06
10–50%	18	1.6	1.8	-0.1	0.28
50–90%	16	2.1	2.9	-0.8	0.063
90–100%	15	4.0	2.4	1.6	0.13

Table S2 Analog of Table S1B with year-specific results for Louisiana CWV sites: mean erosion

2010–2011					
Stem oiling category	n	Mean erosion	Expected when no difference	change from expectation	P-value
0%	16	1.5	1.3	0.2	0.34
0–10%	13	1.1	1.8	-0.7	0.081
10–50%	18	1.1	1.5	-0.4	0.40
50–90%	16	1.5	2.2	-0.7	0.11
90–100%	15	3.4	1.8	1.6	0.040

2011–2012					
Stem oiling category	n	Mean erosion	Expected when no difference	change from expectation	P-value
0%	15	1.6	1.8	-0.2	0.32
0–10%	13	1.1	2.6	-1.5	0.15
10–50%	18	2.7	2.4	0.2	0.41
50–90%	16	2.3	4.0	-1.6	0.21
90–100%	15	6.4	3.4	3.0	0.068

2012–2013					
Stem oiling category	n	Mean erosion	Expected when no difference	Change from expectation	P-value
0%	15	1.6	1.2	0.4	0.21
0–10%	13	1.7	1.7	0.0	0.52
10–50%	18	1.1	1.5	-0.4	0.48
50–90%	16	2.4	2.6	-0.2	0.40
90–100%	15	2.2	2.0	0.2	0.36

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