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Contribution to the Theme Section 'Response of nearshore ecosystems to the Deepwater Horizon Oil Spill'

Oil spill response-related injuries on sand beaches: when shoreline treatment extends the impacts beyond the oil

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ABSTRACT: Studies of oil spills on sand beaches have focused traditionally on the effects of short-term oil exposure, with recovery of sand beach macrobenthic communities occurring within several weeks to several years. The *Deepwater Horizon* spill resulted in chronic, multi-year re-oiling and up to 4 yr of extensive and often intensive treatments. Of the 965 km of sand beaches that were oiled, shoreline treatment was documented on 683 km. Intensive mechanical treatment was conducted from 9 to 45 mo after the initial oiling on 32.4 km of shoreline in Louisiana, and deep beach excavation/sifting and tilling was conducted along 60.5 km in Louisiana, Alabama, and Florida, often along contiguous lengths of beach. Recovery of sand beach invertebrate communities from the combined effects of oiling and treatment would likely be delayed by 2 to 6 yr after the last response action was completed. We introduce the concept of 'Response Injury' categories that reflect both intensity and frequency of beach treatment methods. We use the literature on similar types of disturbances to sand beach communities (foot traffic, vehicular traffic, wrack removal, beach nourishment) to describe the expected impacts. Temporal patterns of response-related disturbances can affect seasonal recruitment of organisms and the overall rate of ecosystem recovery from both oil exposure and treatment disturbance. This concept provides a framework for specifically assessing response-related impacts in future spills, which has not been considered in previous injury assessments.

KEY WORDS: *Deepwater Horizon* · Oil spill · Sand beach · Shoreline treatment · Shoreline cleanup · Impact · Recovery

INTRODUCTION

Approximately 70% of the land–sea margin globally, and the predominate portion of the land–sea margin in the northern Gulf of Mexico, consist of exposed sand beaches (Rakocinski et al. 1991, Dugan et al. 2010). This generally narrow, but ubiquitous landform supports a diverse, but cryptic, biological community that, along with the physical structure of the beach, provides an array of ecosystem services, some of which are widely recognized and exploited commercially, some of which are not. The list of recognized services provided by sand beaches includes: (1) sediment storage and transport; (2) wave dissipation and buffering during storms; (3) scenic vistas and recreation; (4) groundwater filtration; (5) nutrient mineralization and recycling; (6) maintenance of biodiversity and genetic resources; (7) carbon transfer from primary producers and decomposers to species of broad public interest, such as birds and fish; and (8) functional links between terrestrial and marine environments (Defeo et al. 2009). Many of these services can be altered, diminished, or destroyed by oiling of the beach and shoreline cleanup actions to remove the oil.

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The *Deepwater Horizon* (DWH) oil spill resulted in the oiling of 965 km of sand beach habitat from Florida to Texas, USA (Fig. 1; Nixon et al. 2016). Oil first began stranding in May 2010, which was soon followed by shoreline cleanups. Oil stranded in discontinuous waves over a 3 mo period, resulting in the incorporation of oil into the sediments in supratidal, intertidal, and nearshore subtidal habitats, at depths that could be greater than 1 m (Michel et al. 2013). Over time, these oiled sediments became remobilized, broken into oil:sediment balls, and subsequently were reburied as the beaches eroded and then accreted as part of the normal beach cycle. Most of the initial oil stranded when the beaches were in an eroded state, following a series of strong winter cold fronts from the prior year. Gulf beaches erode during the approach of these winter cold fronts by a combination of strong north winds that move sand from the backshore to the upper beach face, followed by southerly winds that transport some of the sand into the subtidal nearshore once the fronts have moved through (Dingler et al. 1992). Subsequent accretion following these erosional events deeply buried some of the DWH oil, which persisted in spite of the passage of several hurricanes (Michel et al. 2013). Beach profile data collected by field teams documented this post-oiling beach accretion from Louisiana to Texas (Deepwater Horizon SCAT Program unpubl. data). Removal of buried and exposed oil required extensive and prolonged uses of mechanical and manual treatments to meet cleanup endpoints. Cleanup endpoints were defined by a maximum amount of oil from the DWH spill (MC-252 oil) that could remain in the beach habitat (Table 1). On many beaches managed by federal agencies as part of national park lands or national wildlife refuges, the decision was made to have less stringent cleanup endpoints and forego intensive mechanical treatment.

Initially, most surface oil was removed using manual methods. However, by the fall of 2010, the Unified Command, composed of the US Coast Guard, BP, state, and local representatives responsible for directing the response, decided to use mechanical sifters to minimize sand removal, which was implemented mostly on amenity beaches in the 3 eastern states of Florida, Alabama, and Mississippi. The decision was made because of the large extent of shoreline to be cleaned, the deep burial of the oil, the patchy distribution of oiled sediments, the stringent cleanup endpoints for amenity beaches, and the push to open beaches in time for the 2011 tourist season. Mechanical sifting was conducted at night when the oiled sediments were cooler and less likely to break up as they passed through the screens. Night-time operations had the added potential impact to nocturnal fauna, such as sea turtles, ghost crabs, and wrack-associated species.

Another consequence of the deep burial of the oil was that most intensive removal operations were conducted in the supratidal zone. The large number of vehicles used during the response traveled mostly in the supratidal zone. Though efforts were made to restrict vehicles to certain corridors, incipient dune areas were heavily trafficked. Manual removal was conducted in all tidal zones. Many of the oiled sediments were referred to as surface residue balls, because they contained only about 10% oil but were cohesive. Long-reach tracked backhoes operated at the water line in the intertidal zone during efforts to remove submerged or buried oil:sediment mats from nearshore subtidal areas.

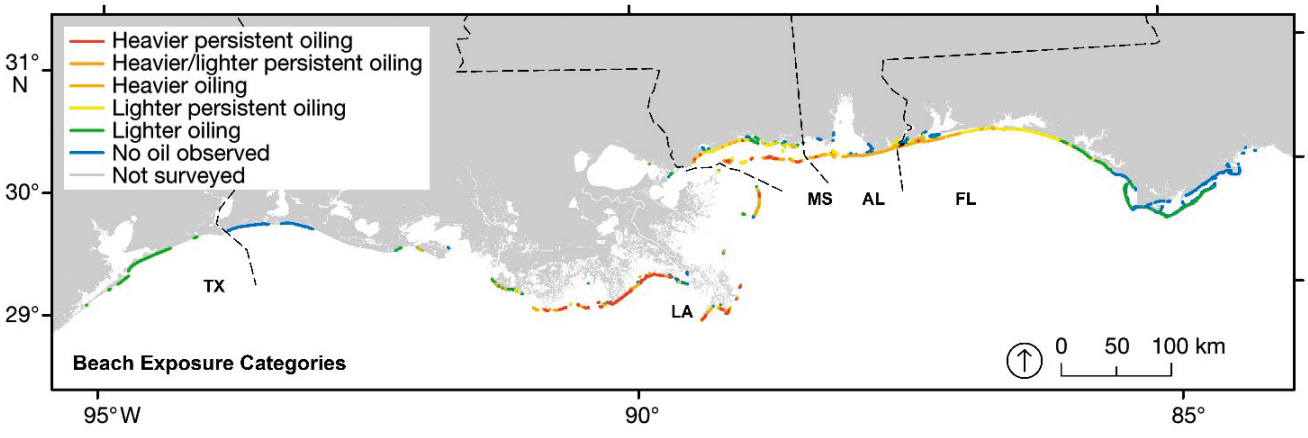

Fig. 1. Distribution of the maximum oiling category for all beaches affected by the *Deepwater Horizon* (DWH) oil spill. Compare with the maximum Response Injury (RI) in category per year (Fig. 6). See Nixon et al. (2016) for more detail on how oiling categories were defined and determined

Table 1. Cleanup endpoints for sand beaches for the *Deepwater Horizon* oil spill. SRB: surface residue ball

Shoreline type	Surface oil	Subsurface oil
Eastern states: Florida, Alabama, Mississippi		
Residential and amenity sand beaches	No visible MC-252 oil, or…*	No visible MC-252 oil, or…*
Non-residential or non-amenity sand beaches	<1% visible surface oil and oiled debris, and no SRBs >5 cm diameter, or…*	No subsurface oil exceeding 3 cm in thickness and patchy (<50%) distribution that is greater than oil residue, or…*
Beaches in special management areas (state and federal wildlife refuges, parks, wilderness areas)	Subject to direction of special area managers: <1% surface oil and oiled debris, and no SRBs >2.5 cm, or…*	Subject to direction of special area managers: no subsurface oil exceeding 3 cm in thickness and patchy (<50%) distribution that is greater than oil residue, or…*
Louisiana		
Residential beaches	No visible oil that is MC-252, or…*	No visible MC-252 subsurface oil above stain, or…*
Non-residential beaches and non-federal special management areas	<1% distribution of oil and oiled debris, or…*	No subsurface oil exceeding 2.54 cm in thickness and patchy (<50% distribution) that is greater than oil residue, or…*
Beaches in federal special management areas	<1% surface oil and oiled debris, or…*	No attempt to remove subsurface oil

*[or…] as low as reasonably practicable, considering the allowed treatment methods and net environmental benefit

Most mechanical removal operations in Florida, Alabama, and Mississippi were terminated by March 2011; however, mechanical removal methods were intermittently implemented until 2013 for some shorelines in Alabama. Due to beach erosion concerns in Louisiana, mechanical methods were initially used only on 1 amenity beach. However, mechanical excavation methods were extensively used both in the intertidal and supratidal zones in Louisiana during 2011 to 2012, to remove deeply buried oil that had persisted on several beaches through several hurricanes. Mechanical augers on small tracked vehicles were used extensively to delineate buried oil for removal; for example, nearly 38 000 auger holes were excavated in a 10 × 10 m grid between November 2012 and August 2013 on several beaches in Louisiana. Manual removal methods continued at different frequencies for years; active shoreline treatment operations were deemed complete in Florida, Alabama, and Mississippi in June 2013 (lasting 3 yr), and in Louisiana in April 2014 (lasting nearly 4 yr).

As part of the natural resource damage assessment (NRDA) for the DWH spill, the impacts of oil exposure and subsequent treatment activities on sand beach communities were assessed (Deepwater Horizon Natural Resource Damage Assessment Trustees 2016). Many of the papers in this Theme Section describe the field studies conducted for injury assessment of coastal resources. However, no field studies were conducted for sand beach faunal communities impacted by the spill for several reasons. First, the approach often used in past NRDA cases where sand beaches were oiled was to rely on: (1) maps of the degree of oiling based on data collected as part of the response to document exposure; (2) the literature to determine impacts by oiling category; and (3) the life histories of sand beach communities to predict recovery once the oil was removed. This approach, while expedient and effective for many spills, potentially underestimates the effects of extensive or intrusive response activities to the sand beach community. Second, the Trustees also had not anticipated the extended duration of repeated oil deposition nor the intensity and duration of response activities to remove the oil. This increased the complexity of integrating any potential sand beach faunal field studies over much of the northern Gulf of Mexico during the most critical time periods of the response. Finally, field survey study design was further complicated by a lack of baseline sand beach faunal community information for many of the impacted beaches. The Trustees determined it was more effective to consider alternative assessment strategies that relied on previously used techniques but also allowed them to consider intensity of disturbance on the beach community. Therefore, in the absence of any field measurements on species composition, abundance, or density in impacted versus control areas, the injury assessment had to be based on existing data, which consisted of (1) extensive documentation of oiling degree and duration, (2) detailed information on treatment methods, location, and duration, and (3)

estimated impacts to beach macrofaunal communities from a synthesis and review of the literature for similar types of oiling and disturbances.

Bejarano & Michel (2016) reviewed the oil spill literature on sand beaches and found that the extent of impacts and intervals to recovery vary according to the degree of oiling. Recovery intervals ranged from several weeks to several years, with longer recoveries for spills with long-term oil persistence or when there was no oil cleanup. Studies of 2 spills were considered most relevant because the oil weathered at sea during long-distance transport before stranding on shore: the 1979 *Ixtoc 1* blowout of crude oil in the Gulf of Mexico which affected similar fauna in southern Texas; and the 2002 TV 'Prestige' spill of heavy fuel oil off Spain. For the *Ixtoc 1* spill, Kindinger (1981) and Tunnell et al. (1982) report a wide range of survival of infauna from before and after the spill across the 13 beaches they sampled. At 7 of these 13 beaches, intertidal infauna abundances ranged from 85 to 97% lower after the spill. Three beaches showed a range from no change to modest increases in abundance (0–19%). The remaining beaches decreased in intertidal infaunal abundance (21–74%). For the 2002 TV 'Prestige' spill, de la Huz et al. (2005) and Junoy et al. (2005) reported decreases of 60 to 85% in the more abundant species; however, Junoy et al. (2013, 2014) concluded that recovery occurred within 1.5 yr. Even these most relevant case studies have limited value to injury quantification because of the following unique conditions for the DWH spill: (1) the extensive spatial scale of affected beaches; (2) the contiguity of oiled beaches over long distances; and (3) the extended time interval over which beaches continued to receive oil. Furthermore, because the DWH spill response included extensive and intensive sand beach treatment for up to 4 yr after the initial oiling, we could not rely on the oil-impact literature alone for injury assessment. Therefore, we developed the concept of Response Injury (RI) as a category of sand beach injury to account for impacts from intensive and prolonged shoreline treatment to meet stringent shoreline cleanup endpoints during the DWH response, which had not been specifically addressed in previous injury assessments.

METHODS

Compilation of the types of response disturbance

Determination of response injuries followed a logical process (Fig. 2). The first step was to compile all available information on the types of response activi-

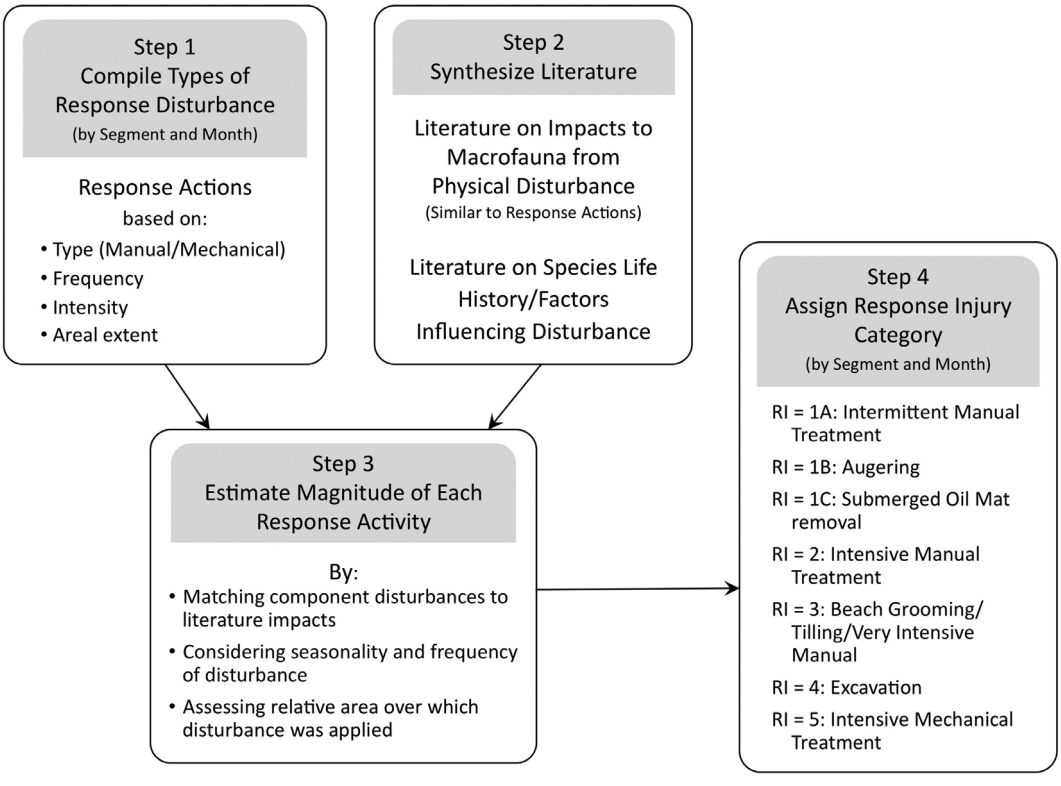

Fig. 2. Logical process for assigning Response Injury (RI) categories, as described in the 'Methods' (also see Table 3)

ties conducted on sand beaches that would disturb beach fauna. The Operations Branch of the Response Organisation generated daily to weekly reports that documented the number of workers, type of equipment, pounds of material removed, and other information for each shoreline segment by day. These reports were less organized early in the response; however, there were many other types of reports generated by monitors that were used as well. Shoreline treatments were assigned and tracked based on shoreline segments that were established by the Deepwater Horizon Unified Command very early in the response. In Florida, Alabama, and Mississippi, shoreline segments were usually about 500 m long; in Louisiana, they could be several kilometers long. We compiled treatment method and the number of times it was conducted on a segment per month into spreadsheets for each state.

Literature compilation

Next (as shown in Fig. 2), an extensive array of published and unpublished documents was consulted to estimate the injuries induced by the types of response activities employed (described in detail by Michel et al. 2015). Literature searches were conducted using PubMed, Web of Science, Google Scholar, and other databases available through EndNote® online search tools. Each citation was reviewed to select those most applicable. The EndNote® library for the references that we reviewed included over 200 papers (Bejarano et al. 2015); however, herein we cite the 39 most relevant references. We summarized key biological information of sand beach fauna in the northern Gulf of Mexico by beach zone, association with and use of wrack, role in trophic transfer, reproductive mode (bentho-pelagic or brooding), seasonality, and prey. The importance of life history in predicting expected recovery from oiling and response injuries resulting from the DWH oil spill is discussed by Michel et al. (2015).

Literature on sand beach communities

Based on our review of literature sand beach communities, Hooper (1981), Kindinger (1981), Rakocinski et al. (1991, 1998a,b), Yáñez-Arancibia & Day (2004), Cobb & Arnold (2008), and Irlandi & Arnold (2008) provided the most information relevant to northern Gulf of Mexico beaches. These studies show that sand beach macroinvertebrates live in a high-energy environment with frequent sand movement, and display a high degree of spatial and temporal variability that is controlled, in part, by wave energy, beach slope, grain size, salinity, and organic content. Globally, many studies (e.g. McLachlan & Jaramillo 1995, Defeo & McLachlan 2005, Dugan et al. 2011, Schlacher et al. 2008) have demonstrated that the structure and nature of the habitat, fauna, and services offered by the supratidal and intertidal (= supralittoral and littoral) differ substantially (Fig. 3). Considering these 2 beach zones separately is also required for our purposes, as most mechanical beach cleanup activities occurred in the supratidal zone, with the notable exceptions of where intertidal and subtidal oil mats were removed and dredging occurred, although manual removal occurred in all zones. Thus, separating the beach into supratidal and intertidal zones allowed us to assign a response injury to the appropriate spatial beach component.

The supratidal zone is the elevated portion of the beach where wrack accumulates because it is infrequently inundated by tides and wave run-up. Wrack, which generally consists of *Sargassum*, *Spartina* stems, and subtidal vascular grasses in the northern Gulf of Mexico, supports a community of invertebrates consisting of terrestrial, semi-terrestrial, and marine species. The terrestrial species (air-breathing species for which the majority of the life cycle occurs in terrestrial or freshwater habitats) include insects

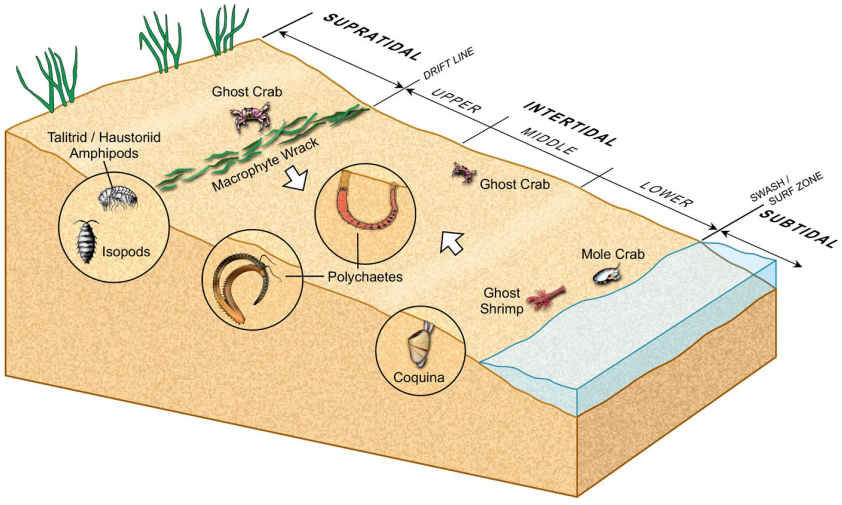

Fig. 3. Distribution of representative sand beach invertebrates. The 3 zones of the intertidal zone grade into each other and are not necessarily rigid in their extent. The fauna typical of the middle intertidal zone is a combination of those found in the upper and lower intertidal zones (represented by white arrows)

(springtails, flies, beetles, and ants) and chelicerates (spiders and mites). The semi-terrestrial species (air-breathing through moistened gills but dependent on saline waters for part of their life cycle) include several species of talitrid amphipods and ghost crabs. The marine species (water-breathing through gills and dependent on saline waters for all of their life cycle) include haustorid amphipods and some polychaetes. These organisms shred the wrack while feeding and are, themselves, often consumed by shorebirds, passerines, and mammals. Wrack-associated organisms may comprise up to 40% of intertidal species and represent an important prey source for higher trophic levels (Dugan et al. 2003). Shredding of the wrack produces fine particulate organic matter that subsequently is degraded by bacteria, releasing the bound nutrients. Predation of this community primarily directs carbon transfer into terrestrial food webs. The supratidal community includes ghost crabs as well, although they do not depend directly on wrack because they are omnivores capable of feeding on marine and terrestrial plants and animals as well as on carrion.

The intertidal beach community differs from the supratidal community in species composition, nutritional foundation, and fate of trophic transfer. The standing invertebrate biomass in the intertidal greatly exceeds that occurring in the supratidal zone (Raffaelli et al. 1991, Colombini & Chelazzi 2003, Janssen & Mulder 2005). In the northern Gulf of Mexico, the intertidal benthic community consists entirely of marine species and is dominated by coquinas, mole crabs, polychaetes, and haustorid amphipods. The majority of these species are suspension feeders relying on beach or surf diatoms as their primary source of nutrition. They are important prey for shorebirds. Fish, especially juveniles of several species, prey on these invertebrates when the beach is inundated. Consequently, trophic transfer of carbon and nutrients from this part of the beach enters into both terrestrial and marine food webs.

Literature on response activity impacts

For the different sand beach treatment activities used during the DWH response, component disturbances specific for that response were identified (Table 2), and the literature on similar types of disturbances was summarized. Intertidal communities on sand beaches are frequently considered tolerant to disturbances because the fauna are well-adapted to the dynamic beach environment. However, these fauna are directly impacted through cleanup operations by mortality from crushing and desiccation during sediment shifting and removal, and indirectly by

Table 2. Sand beach treatment method descriptions and expected associated impacts to sand beach biota and habitat. Intensity of disruption is represented as * = minor; ** = moderate; *** = major

Description	Foot traffic	Vehicular traffic	Sifting mortality	Wrack removal	Biota removal	Biota desiccation	Wildlife disturbance	Substrate compaction	Shell removal	Equipment spills	Dune damage
Manual treatment methods											
Surface removal by shovels, rakes, sifting tools, and other hand tools to 15 cm	*	*	*	**	*	*	*	*	*		
Deep removal >15 cm deep	**	**		**	*	**	**	**			
Transport of workers, waste materials		*					*	*		*	*
Mechanical treatment methods											
Augering often in a 10 m grid spacing	**	**			*		**	*			
Beach cleaners/sifters to depths up to 50 cm	*	***	***	**	**		**	**	**	*	
Excavators to remove clean/oiled sand	*	***			**	**	**			*	
Stockpiling of clean sand overburden		**				**	**				
Heavy trucks for hauling sand to stationary sifters and back to excavation area		***					**	**		*	
Bulldozers to spread sand at excavation area		***					**	**		*	
Excavators to depths as great as 120 cm, often with wet sifting in screened bucket		***	***			**	**	**	**	*	
Tilling to 30 cm, often with multiple passes		**		**			**	*			*
Dredging							**				
Staging areas, where response equipment was transported on/off the shoreline	**	***					***	***		**	*

altering habitat suitability (substrate compaction, wrack and shell removal), disrupting reproduction and recruitment patterns, and removing food supplies. Response activities during the DWH response were characterized by the 4 categories described below, though we note that these categories will vary depending on the spill-specific response methods.

Foot traffic

Persistent human trampling on beaches results in reduced faunal abundances. Noriega et al. (2012) showed consistent 10-fold decreases in ghost crab abundances between visited and unvisited beaches (actual densities changed inversely with intensity and frequency of human activity). Moffett et al. (1998) demonstrated experimentally that barefoot human traffic reduced the survival of softer-bodied crustaceans and juvenile bivalves in the lower intertidal. Compared to other disturbances, foot traffic effects appear moderate (McLachlan & Brown 2006), although small losses in faunal abundances are consistently observed. Manual removal methods often involved intensive foot traffic (Fig. 4A) collateral with other disturbances (e.g. vehicular traffic, wrack removal, sifting) and occurred in all intertidal and supratidal zones.

Off-road vehicle traffic

Off-road traffic (4-wheelers, cars, and pickup trucks) on sand beaches has been studied extensively. These studies indicate that the effects of off-road traffic on local invertebrate assemblages vary greatly depending on their spatial and seasonal occurrence and abundance, and on their specific life histories. Schlacher et al. (2007) found that ghost crabs, with a soft exoskeleton, are frequently crushed by off-road traffic if their burrows are relatively shallow (5 cm); mortality declined exponentially with burrow depth. Those authors also found that ghost crab densities were higher in areas of low to moderate traffic, while individuals were smaller in heavily impacted areas, suggesting alterations of the population structure. Heavily trafficked beaches also had lower abundance, species richness, and diversity of intertidal macrobenthos, and strong changes in the community structure were driven by the low abundances of cirolanid isopods (Schlacher et al. 2008). Direct crushing appeared to be the main cause of community change.

Fig. 4. Sand beach treatment methods. (A) Manual removal/sifting to 15 cm at Ft. Pickens, Florida, January 2011. (B) Four 'Sand Sharks' at Ft. Pickens State Park, running in tandem and sifting to 45 cm, February 2011. (C) Sifting of sediment piles created by mechanical removal on Grand Terre II, Louisiana, October 2010. (D) Excavation of oil mats at Elmers Island, Louisiana, December 2010

Lucrezi & Schlacher (2010) reported that sand beaches with traffic were slightly hotter and had lower moisture content than beaches closed to traffic, and not only were ghost crabs smaller, but also constructed much deeper and longer burrows, possibly to avoid desiccation. Kluft & Ginsberg (2009) demonstrated that vehicle traffic can degrade beach wrack quality by crushing, scattering, or burying, thus impacting the survival of invertebrates that depend on this habitat for food and shelter. Open-beach species (i.e. beach hopper and wolf spider) were more susceptible to disturbance than wrack inhabitants (enchytraeid oligochaetes and tethinid flies). Gastropods, on the other hand, appeared to be more resistant than soft-bodied invertebrates (mysids and isopods) to vehicle traffic (van der Merwe & van der Merwe 1991). Aside from direct crushing, heavy traffic decreases invertebrate abundance by reducing food availability (including wrack), increasing species displacement, disrupting the intertidal habitat and the physical properties of the sand substrate, and increasing invertebrate exposure to predators from the continuous maintenance of burrows (Schlacher et al. 2007, Kluft & Ginsberg 2009). Many of these factors in turn can influence recruitment.

Compaction increases the bulk density of the substrate and reduces the interstitial space, thereby altering the capillarity, water retention, permeability, and exchange of gases and nutrients within the substrate (USACE 1989, Defeo et al. 2009). Compaction also increases the resistance to burrowing, which can impact burrowing behavior and reduce the abundance of burrowing fauna (Lindquist & Manning 2001). The overall impacts of compaction can be translated into reduced substrate productivity and microhabitat suitability (Lindquist & Manning 2001).

Beach grooming and wrack removal

Some of the mechanical beach cleaners used during the DWH response (Fig. 4B) were modified from those used for beach grooming on amenity beaches. While operated in a similar manner for beach grooming, these machines were set to extend 30 to 45 cm into the beach sand rather than 0 to 15 cm used during normal grooming, thus increasing impacts to the infaunal community. Screens of 6 to 25 mm were used. Beach grooming has significant effects on the community structure (depressed species richness, abundance, and biomass) of wrack-associated fauna, causing substantial reduction of prey for higher trophic levels (Dugan et al. 2000, 2003, Defeo et al. 2009), and, depending on the spatial scale of grooming (<1 to 100 km), the effects can be noticed at scales ranging from weeks to years (Defeo et al. 2009). Mechanical raking (0–3 cm penetration) for wrack removal on the upper intertidal zone at Padre Island National Seashore, Texas, lowered the mean density and biomass of all macrofauna within 3 d of raking, and the density and biomass of the amphipod *Orchestia grillus* and polychaetes up to 10 d after raking, compared to unraked areas (Engelhard & Withers 1997).

Removal of wrack with mechanical beach cleaners at 2 tourist beaches reduced the percent total organic matter in the upper beach zone and caused high community stress (i.e. lowered invertebrate diversity, the number of distinctive taxa, and genetic diversity were caused by replacement of species with a higher number of opportunist species), compared to non-tourist beaches (Gheskiere et al. 2005). The removal of the top 5 cm of sand surface with mechanical beach cleaners (Gheskiere et al. 2006) caused significant changes in the total abundance and community structure immediately after cleaning by reducing the abundance of dominant nematode species and harpacticoid copepods, although they recovered completely in the following 2 tide cycles. In Sweden, cleaned beaches had a much lower level of organic carbon than un-cleaned beaches, and the most intensively cleaned beaches had lower total benthic biomass (Malm et al. 2004). However, biodiversity and community structure were not significantly different between cleaned and un-cleaned beaches.

Studies of the effects of beach cleaning in Poland suggested that trampling and mechanical cleaning may have contributed to the disappearance of air-breathing amphipods or sandhoppers from the most frequently visited beaches (Weslawski et al. 2000a,b and citations therein). Furthermore, wrack removal from the upper layer of sand and sand sifting through a 5 mm sieve effectively removed important food sources for key beach fauna, which are linked to the disappearance of macrofauna and the decline of their predators. Weslawski et al. (2000a) indicated foot traffic (3000 steps m^{-2} d^{-1}) caused sufficient beach fragmentation and mixed debris with sediment down to 10 to 30 cm.

Sediment removal and placement

Cleanup operations involving translocation of large volumes of sand (Fig. 4C,D) can be equated with beach nourishment projects, as sand is

mechanically moved and redistributed on the beach surface, resulting in sizable changes in geomorphology (beach profile, sediment composition, substrate compaction), as well as in temporary changes to the beach inhabitants. Studies following beach nourishment projects and related activities found: (1) slow recovery of an intertidal clam (*Donax* spp.) population after a nourishment project that replaced the original substrate with sediment containing high levels of shell fragments (Peterson et al. 2000); (2) slow recoveries of macrobenthos after a nourishment project that increased concentration of fine sediments (Rakocinski et al. 1996); (3) large impacts on invertebrate populations for nourishment projects that coincide with the recruitment period of indicator species (Cobb & Arnold 2008); and (4) low species richness and equitability compared to pre-nourishment levels (Reilly & Bellis 1983). Major disruptions of the sand beach surface can have significant impacts at population (demography and dynamics), community (species richness), and ecosystem (functional processes, nutrient flux, trophic dynamics) levels (Defeo et al. 2009). Furthermore, reduction in the abundance and biomass of dominant species has been linked to disturbances in the foraging behavior of shorebirds and to reduced habitat productivity (Peterson et al. 2006, Defeo et al. 2009). However, others (Nelson & Collins 1987) have reported no measurable effects on indicator species attributable to nourishment projects.

Beach nourishment can cause immediate ecological damage to the resident sand beach invertebrate community including complete mortality of resident intertidal biota. Bilodeau & Bourgeois (2004) found that 2.5 yr after nourishment at the Isles Dernieres barrier islands of Louisiana, the ghost shrimp *Callichirus islagrande* did not have the large densities seen at reference sites with well-established populations. Only a few juveniles and 1 ovigerous female were found on the nourished beach, indicating that the population showed no indication of recolonization or recruitment. The lack of recolonization was attributed to changes in the sediment composition.

Mechanical disturbance, similar to that produced by many response activities, has been demonstrated to have direct, negative effects on beach macrofaunal populations. Lindquist & Manning (2001) evaluated impacts of beach nourishment and mechanical redistribution of beach sand (bulldozing) and found significant declines in the abundance of ghost crabs 6 to 8 mo post-bulldozing. Bulldozing also reduced the abundance of mole crabs, though these changes were not statistically significant from controls. Other species (i.e. coquina clams, spionid polychaetes, and amphipods) appeared to have escaped the impacts of bulldozing as their abundances resembled those of control beaches. Peterson et al. (2000) found that both beach nourishment and bulldozing had quantifiable effects on intertidal species 5 to 10 wk post-treatment compared to control beaches. Nourishment reduced the density of 2 dominant taxa, mole crab and *Donax* spp. by 99 and 86%, respectively, possibly by altering the composition of the substrate, whereas bulldozing reduced the abundance of mole crabs and active ghost crab burrows by 37 and 65%, respectively, probably by changing beach morphology. Peterson et al. (2006) also attributed large mass mortality of benthic macroinfauna to beach filling. Over several months post-treatment, *Donax* spp. and amphipods had much higher abundances (85 and 89%, respectively), and ghost crab burrow density across the beach was up to twice as high on undisturbed control beaches. In contrast, ghost crab summertime recruitment appeared to have been inhibited on filled beaches. In Australia, beach nourishment caused the elimination of an amphipod with signs of recovery seen only 9 wk later (Jones et al. 2008). In South Africa, excavation of sand to a depth of 30 cm caused temporary changes in the abundance of macrofauna; this community required 7 to 16 d to recover following a single disturbance event (Schoeman et al. 2000).

From the literature, it is clear that species susceptibility to impacts from the types of disturbances similar to sand beach treatment methods is largely dependent on individual body size, fragility (soft vs. hard bodies), population turnover rates, and burrowing behavior (deep vs. shallow). Generally, large-scale operations would be more detrimental to species that: (1) brood their young; (2) have a soft exoskeleton; (3) have larger sizes and lower turnover rates; (4) build shallow burrows; (5) have seasonal reproductive cycles that coincide with cleaning activities; (6) occur at high densities in soft, non-compacted sand; and (7) are more closely associated with the substrate, and therefore are more strongly impacted by changes in the structure of the sand matrix (compaction). The fauna comprising sand beach communities along the northern Gulf of Mexico shoreline have many of these characteristics (Shelton & Robertson 1981, Britton & Morton 1989), and impacts would be proportional to both the temporal frequency and spatial extent of disturbances.

RI assignment to the shoreline

We developed 5 RI categories for the DWH response (shown in Fig. 2 and defined in Table 3) that depended on disturbance type, intensity of the disturbance, the frequency of use, and, based on a literature review, the likely effects of each specific disturbance. The scale is ordinal; actual impacts vary substantially within each category. The compiled data on shoreline treatment methods by segment and date were used to assign a monthly RI category for each segment.

For each month and segment, we derived an estimate for the impacts to sand beach ecosystem services by considering: (1) the levels of intensity of the response activities; (2) where the activity occurred on the beach; (3) whether the area where the activity was applied was spatially extensive or narrowly restricted, and (4) whether the activity was coincident with oiling of the beach (May to September 2010).

For both intermittent and intensive manual removal (RI = 1A and 2), during the period when the oil was coming ashore, cleanup crews aggressively removed all wrack, whether it was visibly oiled or not. Removal of wrack would have also removed many wrack fauna and their essential habitat. Consequently, in cases where complete or near complete removal of the wrack and associated fauna occurred, there would be a very high loss of the faunal community in the supratidal. Wrack removal or disturbance along 100s of km of contiguous shoreline would have far greater faunal impacts, and ecosystem recovery would be much slower, than those occurring along isolated beaches disturbed on smaller spatial scales (S. Fegley & J. Michel unpubl.). Later, when monitors

Table 3. Response Injury (RI 1–5) categories, descriptions, intensity by the 4 major disturbance types, and overall impacts on sand beach ecosystem services

RI	Description	Foot traffic	Vehicular traffic	Sediment disruption/ excavation	Wrack removal	Overall impacts to beach fauna
1A: intermittent manual treatment	Manual only, lower frequency (<20 visits mo^{-1}), includes vehicle traffic for transport of workers and waste	Very low to low	None to low, depending on how many vehicles were present	None to low	Prior to 1 October 2010 - high;	High
					After 1 October 2010 - low	Very low (non-amenity beaches only)
1B: augering	Mechanical augering	Low to moderate	High due to use of the tracked auger	Very high in augered pits	Low. Incidental physical disruption only	Very low
1C: submerged oil mat removal	Long-armed backhoes on tracks operating in the intertidal zone at the water line to remove subtidal oil mats	Moderate	High due to use of tracked vehicles and towed equipment	High	None to very low	Low
2: intensive manual treatment	Mostly manual (but includes walk-behind sifters for any duration), higher frequency (>20 visits mo^{-1}), includes vehicle traffic for transport of workers and waste	Moderate	None to low, depending on how many vehicles were present	None to low	Prior to 1 October 2010 – high	High
					After 1 October 2010 - low	Very low (non-amenity beaches only)
3: beach grooming/ tilling/very intensive manual	Treatment at least twice mo^{-1} with a mechanical beach groomer that would sift the sand to a depth of 30 cm; all tilling operations; intensive manual removal of large amounts of oiled materials	Moderate	High	High	High due to direct removal and physical disruption	High
4: excavation	Treatment at least twice mo^{-1} with a mechanical device, and at least once mo^{-1} beach sand was mechanically removed from the beach and sifted; mechanical removal of clean sand for manual removal of oiled sand	Moderate	High	High	High	High
5: intensive mechanical treatment	Extensive deep (>30 cm) mechanical treatment, staging areas, and dredging	Moderate	High	High	High	High

were assigned to the cleanup crews, clean wrack removal was minimized, losses to the faunal community would be reduced, but only to non-amenity beaches, because amenity beaches had historically experienced persistent disturbances associated with foot traffic and beach cleaning. For submerged mat removal (RI = 1C), which involved tracked backhoes operating in the intertidal zone, losses would be low because the repeated movement of heavy equipment was limited to small areas of each segment.

More intensive treatments defined in Table 3 include beach grooming/tilling/very intensive manual treatment (RI = 3), excavation (RI = 4), and intensive mechanical treatment/staging areas/dredging (RI = 5) and would have induced extensive mortality within the treatment area by displacement, physical trauma, desiccation, and burial during sand storage and replacement. These activities also included ancillary, extensive foot/vehicle traffic and wrack removal. The extensive use of heavy equipment, such as large dump trucks, tracked backhoes, towed sifters, and bulldozers, during the DWH response was unprecedented in terms of both the spatial extent and intensity (Fig. 4B–D).

RESULTS

Of the 965 km of sand beaches that were oiled, shoreline treatment was documented on 683 km (71%). In Florida, where nearly 80% of the oiling on sand beaches was classified as light and 43% as light persistent, frequent manual treatment (RI = 2) was conducted on 67% of the shoreline (Fig. 5). However, to meet stringent cleanup endpoints for amenity beaches, beach grooming and tilling were conducted in the supratidal along nearly 60 km that had heavier oiling initially but was subsequently buried. In Alabama, there were 2 areas where intensive treatment in the supratidal zone was conducted to remove deeply buried oil that caused persistent re-oiling of the beach. In Mississippi, much of the heavier oiling occurred on the outer barrier islands of the Gulf Island National Seashore, where mechanical methods were restricted. Thus, there was proportionally less response-related impact. On the sand beaches of Louisiana, in spite of over 80 km of heavier persistent oiling, intensive mechanical treatment was conducted on only 32.4 km because of concerns that mechanical treatment would increase erosion on highly erosional islands. Furthermore, because of the remoteness and difficulty of access to many of the barrier islands in Louisiana, only manual removal (RI = 1 and 2) occurred on 140 km, regardless of the degree of oiling. It was only in 2011 and 2012, when the decision was made to conduct mechanical and intensive manual removal to prevent chronic re-oiling, that RI = 5 categories were assigned (Fig. 6).

The maximum RI category for each shoreline segment varied for each year from 2010 to 2014, as did the contiguous extent of treatment in each year (Fig. 6). In 2010, treatments with RI ≥ 2 were conducted throughout the region, with mechanical excavation conducted late in the year along beaches in Florida and Louisiana. In 2011, persistent buried oil was removed by excavation and sifting along Florida and Alabama beaches, and deep excavations were conducted at Fourchon, Louisiana (RI = 5, red lines in

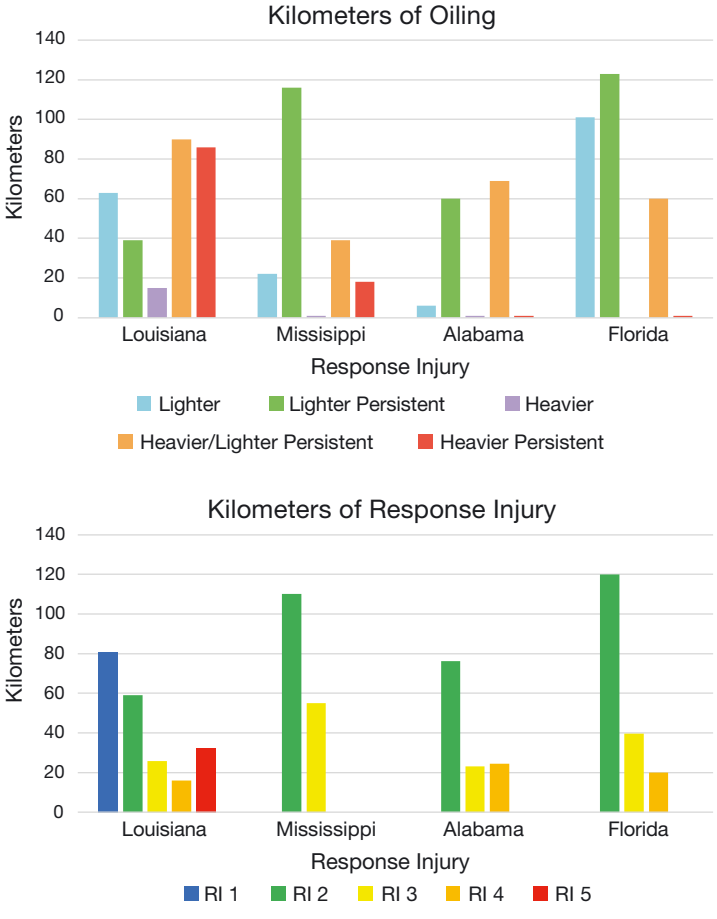

Fig. 5. Length of sand beach by state-assigned (A) oiling category and (B) maximum Response Injury (RI) category. 'Persistent' applies to oiling that persisted on beach for at least 26 wk based on repeat surveys. See Nixon et al. (2016) for more detail on how oiling categories were defined and determined

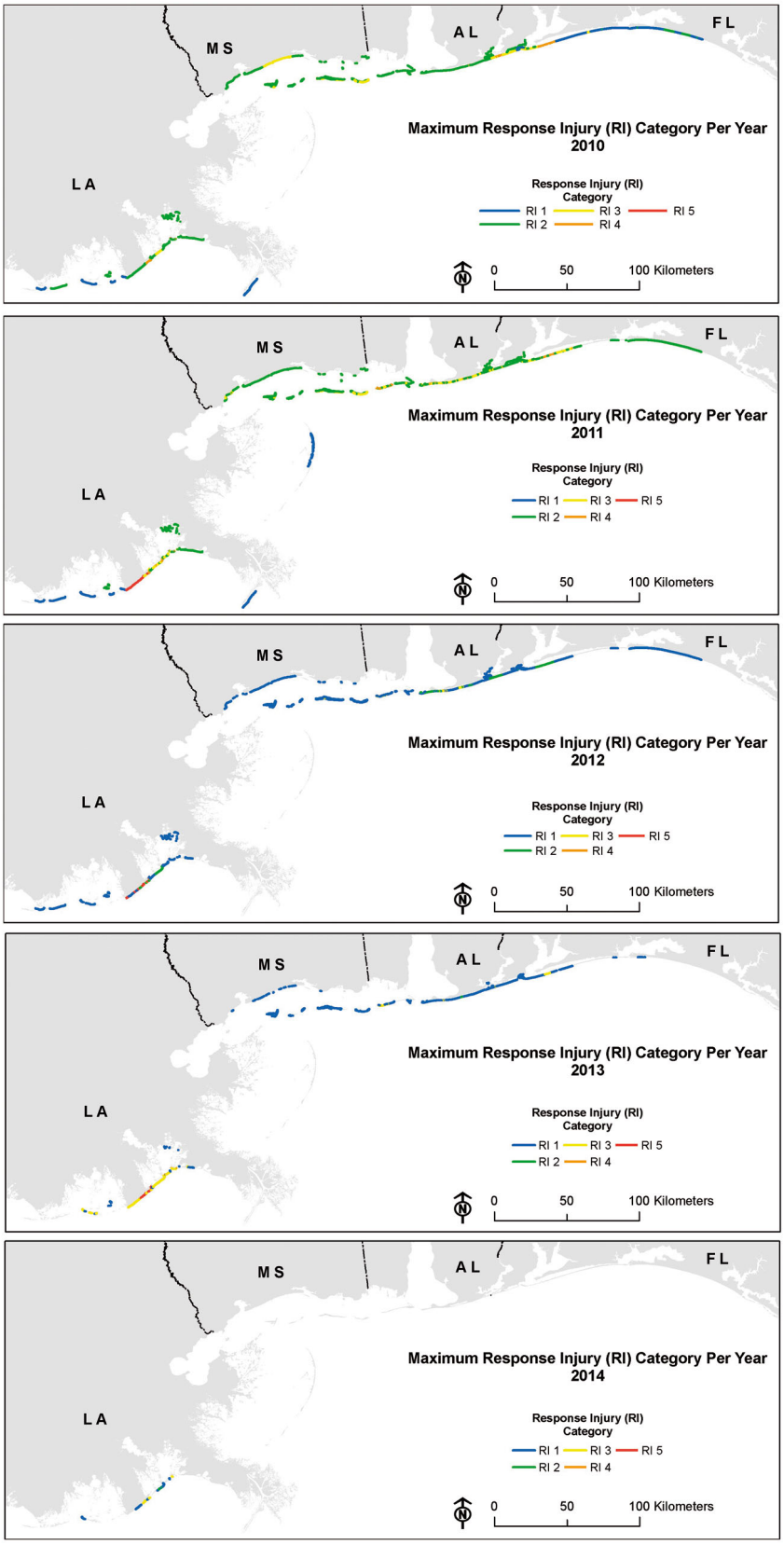

Fig. 6. Maximum Response Injury (RI) category for each beach segment per year

Fig. 6). By 2012, mostly manual removal methods were being conducted, except for some locations in Louisiana. By 2013, intermittent manual removal methods were conducted in Florida to Mississippi, ending in June 2013 when treatment operations were officially terminated on all of these beaches. However, mechanical excavation and intensive manual removal methods were being conducted later in 2013 along Louisiana beaches with persistent buried oil. Louisiana beaches were moved out of response by April 2014, after intensive manual removal of oil on some beaches.

The range of intensity and duration of treatments, and consequently RI and timing for recovery, varied over time and space, which can be illustrated by examining 3 representative areas (Fig. 7). For the lightly oiled beaches of Florida at the eastern extent of shoreline oiling (Fig. 7A), only manual methods were used in all tidal zones, initially at frequencies >20 visits mo^{-1} (RI = 2) until January 2011, when these segments moved into a 'patrol and maintenance' period of less frequent surveys. Workers conducted cleanup operations on every beach segment for 12 mo and on most segments for 19 mo.

Along Alabama beaches, treatment patterns differed. Frequent manual removal only was allowed until early 2011, when there was a push to remove the buried oil. Deep excavations and sifting occurred in the supratidal zone on Dauphin Island, which included large staging and sifting operations, and West Point Island (plotted on the left side of the chart) that lasted from January to March 2011 (Fig. 7B). These types of operations are shown in Fig. 4C. Note the absence of any RI in summer of 2011; these segments were put on 'environmental hold' during bird nesting periods. However, chronic re-oiling on West Point

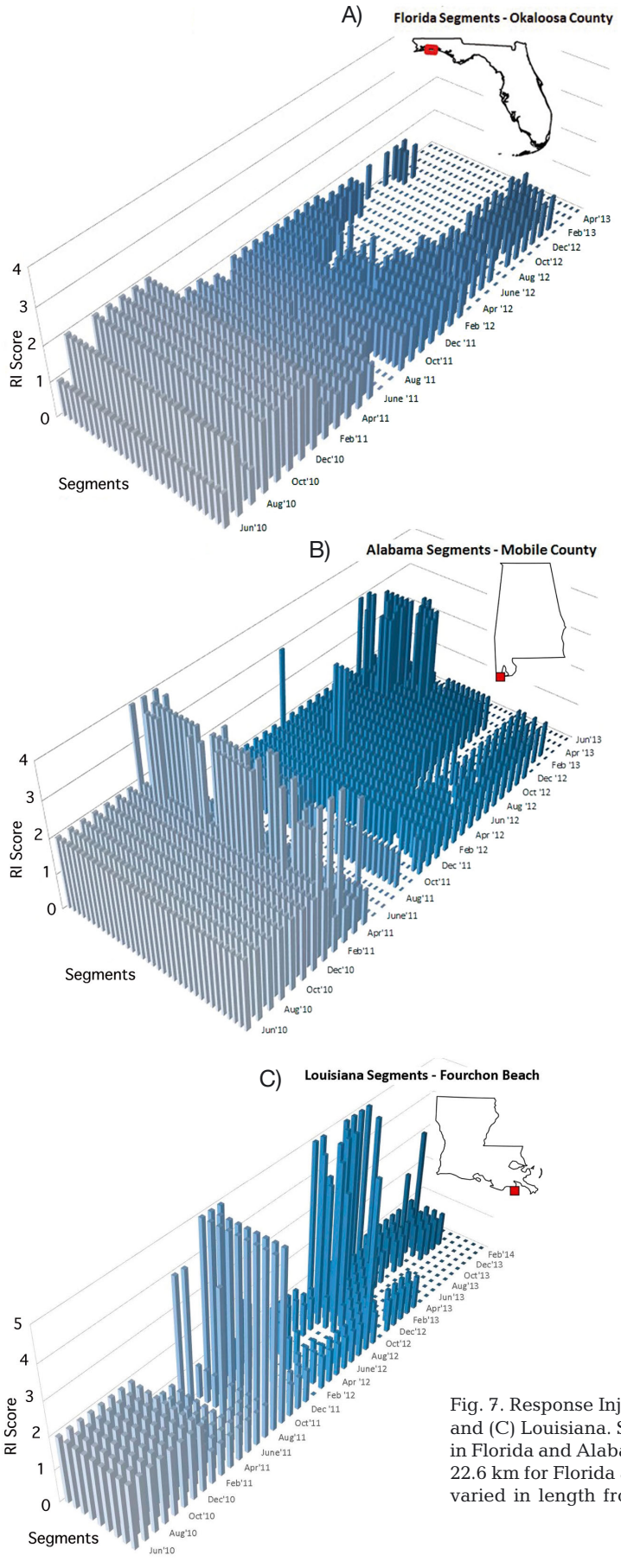

Fig. 7. Response Injury (RI) categories for segments in (A) Florida, (B) Alabama, and (C) Louisiana. Shading is used to improve visualization only. Each segment in Florida and Alabama is about 0.5 km in length, and the entire length shown is 22.6 km for Florida and 18.4 km for Alabama. The segments on Fourchon Beach varied in length from 1.7 to 5.5 km, and the entire length shown is 24.5 km

Island triggered the decision to conduct a second period of intensive mechanical treatment starting in December 2012. Therefore, West Point Island received multiple intensive mechanical removal operations, which would re-set any ecosystem recovery that had occurred after the initial oiling or earlier response activities.

Fourchon Beach, Louisiana, received the heaviest oiling and most intensive treatment (Figs. 6 & 7C). The pattern of treatment shows frequent manual removal (which included extensive vehicular traffic on this beach due to limited access) for >1 yr. These efforts were followed by intensive removal of buried oil in all tidal zones that was partially exposed during Tropical Storm 'Lee' in September 2011 and Hurricane 'Isaac' in August 2012.

These 3 examples (Fig. 7) show the varieties in type, spatial continuity, and duration of sand beach treatments following the DWH oil spill that were conducted for a period of 3 to 4 yr after the oil initially stranded onshore. These operations extended the impacts of the response well beyond that expected from oiling alone. Many studies have found that the sand beach invertebrate community recovers within 0.5 to 5 yr post-spill (as summarized in Bejarano et al. 2011 and references therein). Such recoveries, however, would be interrupted by additional impacts resulting from response activities. The RI impacts to the invertebrate community can exceed those associated with oil exposure (Whitfield 2003, de la Huz et al. 2005, Borzone & Rosa 2009), particularly where intrusive methods were conducted on beaches that were only lightly oiled. The recovery of sand beach invertebrate communities from the DWH spill event was predicted to have been delayed by 2 to 6 yr after the last response action (Deepwater Horizon Natural Resource Damage Assessment Trustees 2016).

DISCUSSION

This work describes a semi-quantitative approach to incorporate impacts to sand beach habitats resulting from shoreline treatment activities, particularly where such activities are very intensive and frequent for long periods of time and along exten-

sive, contiguous lengths of shoreline. The DWH spill was the first case that we are aware of where response injury was determined in addition to and separate from injury associated with the oil exposure for sand beaches. This approach was needed because of the rapid and deep burial of the oil, which resulted in very intensive disturbances to the supratidal zone during subsequent buried oil removal. Most oil spills do not directly affect the supratidal zone (with notable exceptions); therefore, the supratidal sand beach communities are often not included in impact assessments. Only 1 study specifically mentioned the intensity of cleaning activity (heavy machinery and sediment and wrack removal during the 2002 TV 'Prestige' spill in Spain) in addition to the degree of oiling of the beaches that were studied. Macrofauna of the supratidal zone in heavily oiled areas were even more affected where grooming and wrack removal was intense (de la Huz et al. 2005). With the lack of studies on the impacts of intensive and extensive treatment of oiled beaches, our approach of using response data and the disturbance literature provides the only alternative.

We assigned impacts to beach fauna for the different RI categories in relative terms from very low to very high, and we specifically differentiated between amenity beaches (which have heavy foot traffic from high public use and regular beach manicuring that would remove wrack and shallow fauna) and non-amenity beaches (Table 3). For injury quantification for a specific spill, these impacts would be translated into a percent reduction of ecosystem services, followed by appropriate recovery rates depending on the life histories of the beach macrofauna. For each case, it will be important to consider the timing and areal extent of disturbances during intensive beach treatments in determining the recovery rates. Recovery from disturbances with small footprints can be very quick, with recruitment from adjacent, undisturbed areas, as demonstrated in the small, experimental study of the impacts of a single wrack removal event by Engelhard & Withers (1997), who found no significant differences in macrofauna density between raked and unraked areas 2 wk after disturbance ended.

During the DWH response, treatments were conducted along extensive lengths of shoreline and throughout the year. The types of equipment used were of similar or greater weight and footprint, and were involved in activities of greater intensity (both spatially and temporally), than those identified in the literature that we evaluated. As the frequency, intensity, and spatial extent of beach disturbance documented in the aftermath of the DWH oiling exceed the disturbances reported by the majority of studies of off-road vehicles, small field experiments, beach grooming, or one-time beach nourishment projects, greater impacts to sand beach communities can be expected to have occurred on Gulf of Mexico beaches receiving treatment. In consideration of all these factors, we argue that our rankings are conservative and may not fully account for even more extensive impacts originating from beach response treatment activities.

The deliberate, intensive treatment of sand beaches, particularly on amenity beaches, reflects the higher valuation of recreation over other ecological services in high public use areas. Where ecological services are deemed as (or more) valuable than recreation, such as on national parks and wildlife refuges, clean-up methods during the DWH response were much less intensive. The perception appears to be that sand beach communities are tolerant to disturbances and have relatively quick and predictable recovery rates. However, Bejarano & Michel (2016) found few studies of the short-term effects of oil on sand beach invertebrates, and even fewer that documented recovery. Oil exposure and physical disturbances to 965 and 683 km, respectively, of nearly contiguous beach shoreline in the northern Gulf of Mexico likely far exceed the damages documented in individual studies of small areas over short time periods.

The ecological consequences of intensive treatment of sand beaches as we have hypothesized definitely need to be confirmed through well-designed field studies. Results from such studies can and will be used during future responses, to make informed decisions about the tradeoffs in selecting the most appropriate response options. One of the best examples is the study of the severe impacts from use of high-pressure, hot-water flushing on rocky intertidal habitats during the TV 'Exxon Valdez' oil spill versus oil alone, made possible through designation of 'set-aside' study sites where no flushing was conducted (Peterson 2001, Shigenaka 2014). Since then, high-pressure and high-temperature flushing methods are mostly used only on man-made structures such as seawalls and riprap. Studies of various treatment methods on marshes have well documented the impacts of treatment, with the result that often natural attenuation is the preferred response option (Michel & Rutherford 2014). Without studies documenting the impacts of aggressive mechanical removal of oil from sand beaches, it will be difficult to argue for leaving some oil for natural attenuation, particularly on beaches with high ecological value.

Unfortunately, on high-use amenity beaches, the tradeoff analysis is based on economic impacts rather than ecological impact and recovery.

When shoreline treatment is likely to include intensive methods to meet cleanup endpoints, it is important to document the activity as soon as possible. For the DWH response, detailed documentation only occurred during the second year of the response, challenging reconstruction of segment-specific treatment history. Just as teams conduct surveys to document oiling conditions, initially and over time, it is equally important to document the temporal and spatial extent of intensive response actions.

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