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REMEDIATION AND RESTORATION OF NORTHERN GULF OF MEXICO COASTAL ECOSYSTEMS FOLLOWING THE DEEPWATER HORIZON EVENT

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3.1 INTRODUCTION

On April 20, 2010, an explosion on the Deepwater Horizon (DWH) drilling platform and blowout of the Macondo well 1500 m below resulted in the worst marine oil spill on record. An estimated 205 million gallons of crude oil and 260,000–520,000 tons of methane (the energy equivalent of 80–155 million gallons of crude oil) were released into the Gulf of Mexico (GoM) over the following 87 days (Camilli et al., 2012; Joye et al., 2011; McNutt et al., 2011). The DWH blowout was unlike all other well-studied crude oil releases into marine environments. The blowout resulted in a massive shore-bound surface spill, but the discharge of oil and gas under high pressure at extreme depth also resulted in unprecedented deep-ocean persistence of highly dispersed hydrocarbons. Addressing both surface and subsurface conditions posed unanticipated challenges to governmental responses shaped by traditional surface spills (Peterson et al., 2012). Response efforts not only identified major gaps in baseline knowledge of vulnerable ecosystems (Peterson et al., 2012) but also demonstrated that advances in deepwater drilling far outpaced advances in spill containment and shoreline remediation.

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Upon surfacing, oil from the blown Macondo well was transported across the northern GoM, where it grounded on shorelines from Louisiana to Florida. Within 9 days of the explosion on the DWH drilling rig, oil entered Louisiana wetlands at the mouth of the Mississippi River. Within a month, oil had coated shoreline beaches and wetlands throughout the Mississippi River Delta, the largest coastal wetland complex in the continental United States. By the time the disabled well had been capped, oil had grounded on shorelines throughout the northern GoM, including sensitive wildlife refuges like the Chandeleur Islands in Breton Sound, and white sand beaches frequented by tourists in Florida, Alabama, and Mississippi. As of January 20, 2011, surveys of more than 4000 linear miles of the northern GoM coast conducted for the preassessment phase of the Natural Resource Damage Assessment (NRDA) documented 1053 miles of oiled shoreline (http://www.gulfspillrestoration.noaa.gov/oil-spill/gulf-spill-data/). The heaviest accumulations occurred in Louisiana as a consequence of currents and prevailing winds directing much of the oil to the west of the mouth of the Mississippi River. As in other states, oil grounded on to barrier island beaches, but much of the shore-bound oil penetrated into Mississippi River Delta wetland ecosystems. Oil entered marsh and mangrove habitats from the Bird's Foot Delta to Terrebonne Bay, including areas located miles inland from the ocean.

Coastal ecosystems of the northern GoM encompass many of the most productive and biologically important habitats in North America. In addition to supporting sensitive resident species like the brown pelican, these areas shelter the majority of overwintering waterfowl that travel the Mississippi Flyway. Northern GoM coastal ecosystems also provide regulatory services such as storm protection, water filtration, and nutrient capture; provisioning services like finfish and shellfish fisheries; and cultural services including heritage tourism, recreation, and aesthetic value. Coastal habitats (e.g., oyster reefs and marshes) in Louisiana alone support 30% of U.S. fisheries production, and it has been estimated that Mississippi River Delta ecosystems generate at least $12–47 billion in annual benefits (Batker et al., 2010). As an economic asset, the Delta has a minimum value of $330 billion to $1.3 trillion, with 90% of its value attributable to services derived from wetlands (Batker et al., 2010). Oil exposure has placed the ecological and economic well-being of the northern Gulf region at risk by potentially affecting many, if not all, of the valued services provided by these coastal ecosystems.

The federal government, state governments, and the responsible party (British Petroleum (BP) Plc.) mounted a vast and complex response effort soon after oil from the Macondo well was detected in offshore waters. Responders were required to make difficult choices among possible interventions, including what steps to take to prevent oiling of shorelines and removal of oil from sensitive coastal ecosystems. Responders had to decide, for example, whether to contain and recover oil via skimming technologies versus chemically dispersing and burning hydrocarbons from the surface of the water. Experiences during prior oil spills have led to a general understanding that response actions can cause more harm than good. Pressurized hot-water washing of oiled rocky intertidal shorelines during the Exxon Valdez oil spill (EVOS), for example, likely induced greater macroalgal and invertebrate mortality than did exposure to oil (Peterson et al., 2003). Even though consideration is now given to the possibility of unintended outcomes, imperfect knowledge of trade-offs between potential benefits and risks from interventions nonetheless complicated DWH response efforts (Anastas et al., 2010; Peterson et al., 2012).

As in the EVOS, protection and remediation of oiled northern GoM shoreline ecosystems involved weighing potential benefits against risks that interventions intended to reduce damages from oil exposure will instead lead to further injury. Oil removal from coastal wetlands, for example, can reduce acute and chronic exposure of both resident and migratory species, but many traditional removal approaches can cause immediate and enduring damage to fragile soils and sensitive wetland biota. Simply setting foot into salt marshes can result in soil compaction and loss of foundational plants, which can accelerate erosion and lead to permanent loss of marsh habitat. Surface application of dispersants, as was done across northern GoM waters, can reduce shoreline oil accumulations, but it can add petroleum-based (NRC, 2005) into other areas that serve as nursery habitat. Thus interventions, such as diversions from the Mississippi River, can involve protection of one ecosystem at the expense of another. Freshwater diversions intended to provide counterbalancing flows to prevent oil from entering delta wetlands may have collaterally damaged nearby oyster grounds sensitive to low-salinity conditions. Oyster grounds were exposed to the combined influence of oil and freshwater during peak spawning periods, which may have resulted in greater injury to future harvests (i.e., by elevating larval mortality and depressing adult reproduction) than complications from oil exposure alone. Decisions to intervene must also account for how actions may endanger the socioeconomic well-being of communities including cities like New Orleans that depend on coastal ecosystems for income and security.

Despite the possibility of unintended outcomes, interventions were necessary to prevent acute and chronic oil exposure of sensitive biota to oil. As of April 2011, the consolidated fish and wildlife collection report maintained by the U.S. Fish and Wildlife Service (USFWS), which provided daily updates on the number of injuries and deaths of vertebrate species of concern, listed 3596 injuries and 6918 mortalities associated with the spill. In comparison to similar counts following the EVOS disaster, it appears that the Gulf has sustained relatively low levels of damage from the Macondo well blowout (Tunnel, 2010). Acute damages are far less than what many feared would result from the massive release of oil, but little is known about damages that emerge over time and span long time horizons (Peterson et al., 2003). Population- or species-level responses can lag behind a spill when acute exposure to oil and oil-borne contaminants occurs during sensitive life stages. Exposure can interrupt complex life cycles, which can give rise to delayed responses (Peterson et al., 2003). Additionally, lags can emerge if reproduction is depressed by chronic, sublethal exposure or reduced resource availability due to ecosystem-wide disruption of food webs (Peterson et al., 2003).

The persistence of oil in coastal environments more than a year after the DWH blowout indicates that GoM biota have been susceptible to acute and chronic exposure. At the beginning of 2011, the Shoreline Cleanup Assessment Technique (SCAT) program reported that 336 of 1053 miles of oiled shoreline warranted treatment and that at least 83 miles remained heavily to moderately oiled (Owens et al., 2011). Surveys of Louisiana embayments conducted by independent researchers also found that oil persisted under heavily matted vegetation in Barataria Bay marshes, especially in areas where surfaces are not exposed to weathering (Macdonald et al., 2011). Impervious rinds formed on some surfaces exposed to weathering, which can slow aeration and inhibit microbial activity (Deocampo et al., 2011). A survey of beaches on the barrier island chain fronting Barataria Bay found evidence of buried oil in cohesive layers ≥20 cm thick covered by 10–80 cm of clean sand above the water table and vertically diffuse 10–50 cm thick bands of oil below the water table (Fitzgerald et al., 2011). Oiled sand reworked by wave action coalesced into subtidal tar mats in surf zone depressions that could extend for miles off of some areas of the coast, such as Perdido Key beach on the Florida panhandle.

It is now widely recognized that many of the most pressing questions about shoreline impacts and recovery remain unanswered. Created by an Executive Order on October 5, 2010, the Gulf Coast Ecosystem Restoration Task Force has been tasked with addressing this concern by promoting the development of more effective shoreline remediation strategies. Two key conditions have been identified for redressing shoreline damage from the DWH blowout. First, approaches must be science based. And second, approaches must address oiling, erosion, and subsidence. Oil from the blown Macondo well grounded on to areas of the Gulf coast that are experiencing high rates of habitat loss as a consequence of erosion and subsidence. Marshes in Barataria Bay and other heavily degraded deltaic wetlands, for example, are hotspots of habitat loss. Estimates suggest that oiling more than doubled the rate of annual shoreline erosion (Silliman et al., 2012), with most of the additional loss concentrated in highly susceptible wetlands that provide valuable ecosystem services. Thus, response strategies that only address oiling likely will not result in permanent gains.

Here, we assess the prospects for achieving and implementing a forward-minded response policy of postspill habitat remediation and restoration. Focusing on Louisiana coastal marshes that received the heaviest accumulations of oil, we first review the formulation and execution of conventional response strategies for shoreline protection and remediation. We then examine how novel approaches were evaluated and implemented, including several controversial interventions undertaken to protect sensitive coastal ecosystems during the DWH spill. We also overview the down-selection process of shoreline cleanup approaches with reference to studies aiming to improve the process and outcomes of shoreline remediation. Finally, we identify steps that could be taken to promote ecosystem recovery by linking shoreline remediation with habitat restoration, placing emphasis on local sourcing and novel approaches that reduce operational trade-offs and maximize efficiencies.

3.2 SHORELINE PROTECTION DURING AND FOLLOWING THE SPILL

3.2.1 Oil Spill Response Administration and Structure

The National Contingency Plan (NCP) serves as the federal government blueprint for responding to oil spills in federal waters. In accordance with the plan for coastal zones, the U.S. Coast Guard (USCG) was charged with overseeing the DWH oil spill and appointed a National Incident Commander after it was declared a Spill of National Significance. The incident command system (ICS) provided the framework for coordinating the effort of the government agency response organizations (NRT, 2011). The agency organizational structure in the spill response, from top to bottom, included:

- The National Response Team (NRT)—15 federal departments and agencies including the USCG, the National Oceanographic and Atmospheric Administration (NOAA), the Department of Interior (DOI), and the U.S. Environmental Protection Agency (USEPA);
- Regional Response Teams (RRTs) and Rapid Assessment Teams (RATs)—cleanup operation staff led by the USCG and USEPA, which have authority over the use of dispersants; and
- Area Committees (ACs)—local government and environmental agency representatives.

As oil came ashore, RRTs commenced local cleanup operations, guided by preestablished Area Contingency Plans (ACPs). Cleanup proceeded in stages following the SCAT process, using surveys and assessments to create stage-specific Shoreline Treatment Recommendations (STRs) (Santer et al., 2011). RRTs deployed operations task forces to conduct cleanup activities using remediation techniques described by STRs until the segment was judged to require "no further treatment" (NFT) (Santer et al., 2011). Evaluations were made according to group consensus among members of a SCAT team, requiring agreement between representatives from federal, state, and sometimes local government or other shareholders, as well as the team lead and representatives of BP (Santer et al., 2011). The transition from cleanup to long-term recovery follows the Shoreline Cleanup Completion Plan (SCCP) as a framework for providing the final definition of NFT for each shoreline type (DWH UC, 2011a). The SCCP was written collaboratively between the USCG, NOAA, DOI, BP, and the Gulf states except for the State of Louisiana, which refused to sign (Schleifstein, 2011). Having the authority to make response decisions, the USCG federal on-scene coordinator nonetheless enacted the SCCP on November 2, 2011 (DWH UC, 2011a, Schleifstein, 2011).

3.2.2 Limitations of Shoreline Protection through Conventional Offshore Treatment

The chemical and physical composition of oil, as well as ocean and climate conditions, determine the behavior and outcomes of offshore oil spills. The same factors influence the effectiveness of methods for removing oil from the ocean surface (Douglas et al., 1996). Crude oil that rises to the ocean surface is conventionally recovered by response teams with containment boom and skimming technology (Figure 3.1). Surface oil can also be eliminated using fire-resistant containment boom for *in situ* burning or aerial and vessel applications of chemical dispersants. Few feasible options are available for offshore treatment, however, once oil undergoes

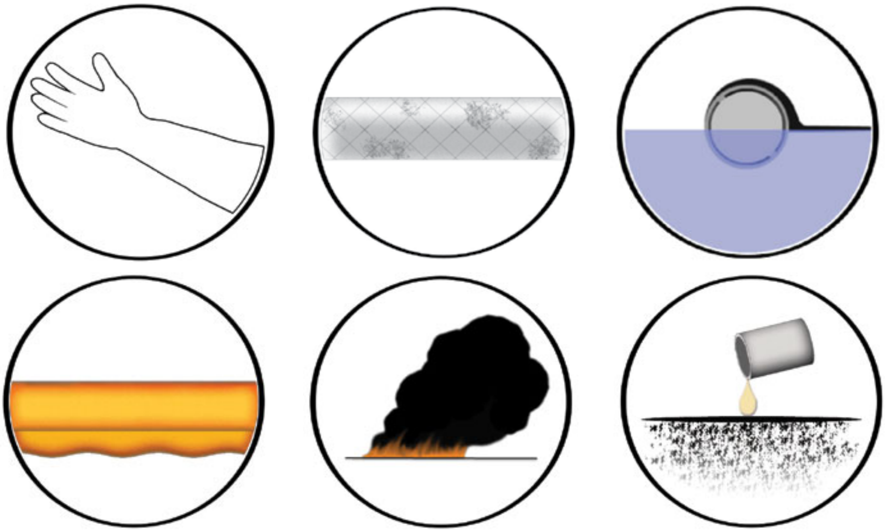

FIGURE 3.1 Conventional oil spill cleanup technology. Top left to right: manual cleanup, polypropylene-filled sorbent boom, and oil skimmer. Bottom left to right: containment boom, *in situ* burning, and chemical dispersant.

weathering through evaporation, dissolution, biodegradation, and photooxidation. Containment, skimming, and burning are not possible as weathered oil loses buoyancy and enters subsurface waters. Surface application of dispersants, which are not designed to break up weathered oil, also becomes unfeasible.

Containment and sorbent boom are often among the first response technologies deployed during offshore surface oil spills. As oil is moved along the surface of the water by current and wind, booming can temporarily hold it in place prior to skimming or burning. Containment boom is either rigid or inflatable, high-strength polyurethane-coated fabric that remains partially submerged below the surface of the water. Containment boom is often outfitted with a vertical skirt that extends below the water surface to improve stability and capture efficiency. White polypropylene-filled sorbent boom works to adsorb oil from the water and is often used in conjunction with containment boom. Boom must be monitored and replaced to keep pace with spill, weather, and tidal conditions. During the DWH event, approximately 4.2 million feet of containment boom and approximately 9.1 million feet of sorbent boom were deployed—considered to be the largest deployment of boom in the history of spill response—to aid in skimming, *in situ* burning, and temporary shoreline protection (British Petroleum, 2010). Eventually, though, monitoring difficulties arising from the magnitude of the deployment, coupled with oil weathering and natural forces (e.g., wind, tide, and currents) overcame the boom, allowing oil to reach sensitive shoreline ecosystems.

Boom is often paired with other technologies to remove oil from the ocean surface. Oil that is contained in rigid boom can be skimmed from the ocean surface into tanks on board a vessel and transported to shore. Conventional skimmers move the surface water toward a recovery system that transfers surface and near-surface layers of oil–water mixtures into a storage tank. Conventional skimming can prove ineffective under adverse weather conditions that complicate containment and that promote subsurface mixing. Equipment availability and personnel costs are two other major limiting factors to skimming oil from the water. During the DWH event, conventional skimming efficiencies were less than 30% oil to water—a figure not uncommon to offshore oil response (British Petroleum, 2010). Oil that is contained in fire-resistant booms also can be burned from the surface with an incendiary charge to promote ignition. Because of public health concerns, burning is typically considered only when mechanical recovery response methods are incapable of controlling the spill (Team, 1998). In Alaska, for example, burning is necessary when ice prevents skimming operations, but waves must be less than 3 ft high, winds less than 20 knots, and the oil slick thickness must be more than 2 mm for burning to commence. Burns release particulate matter as smoke and soot, polycyclic aromatic hydrocarbons, volatile organic compounds, carbon dioxide, and carbon monoxide into air and water (Aurell and Gullett, 2010). In contrast, burning was implemented over nearly the full course of the DWH event. A total of 411 burns removed an estimated 5% (10.3 million gallons) of oil from the ocean surface (Ramseur, 2010), but concerns remain about acute and persistent exposure of coastal populations and response workers to residual contaminants.

Chemical dispersants are not easily paired with containment or sorbent boom. Chemical dispersants are petroleum solvents that move oil from the water surface to the water column by breaking the surface tension or cohesive capacity of the oil, thus breaking it into smaller droplets. The use of chemical dispersants follows a risk-based paradigm with recognized trade-offs between benefits and harm to the environment (see other chapters herein for more detailed discussions of dispersant properties and use). Chemically dispersed oil is more dilute in the water column, which can reduce acute toxicity. Use of dispersants, however, can increase exposure of marine organisms to contaminants that are more bioavailable or more readily absorbed (Bhattacharyya et al., 2003). The total volume of chemical dispersant used in the GoM during the DWH event was approximately 1.8 million gallons. Dispersants were applied on the ocean surface by plane (“carpet bombing”) or boat. The first subsurface application of dispersants approved by the USEPA also was carried out during the DWH event. Approximately 800,000 gallons (44% of the total used) of dispersants were directly injected into oil flowing from the Macondo wellhead in an effort to prevent oil from reaching the surface near the incident site where crews were working to close the well.

Rapid Assessment Teams provided daily on-site prioritization and identification of oiled areas to the Incident Command Center (British Petroleum, 2010). Because of the sheer scale of the surface spill and the response effort, decisions as to whether to contain, disperse, burn, or skim were sometimes based on the proximity of cleanup teams to surface oil. Vessels are typically equipped with only one response technology, so proximity can sometimes outweigh consideration of net environmental benefits of the response approach available for immediate deployment (Baker, 1995). Disparities between need and availability can reduce the effectiveness of offshore recovery efforts (Lehr et al., 2010) and consequently contribute to oil grounding on to sensitive shoreline ecosystems where recovery and remediation can be significantly more challenging than in open ocean conditions.

3.2.3 Limitations of Shoreline Protection and Conventional Onshore Treatment

The magnitude of the DWH surface spill and limitations of offshore prevention and containment measures (characterized as "keeping it out" strategies) required implementation of measures to remediate oil contaminated shoreline (characterized as "getting it out" and "getting rid of it" strategies) (USNRT, 2010). Stage I and II shoreline cleanup responses were implemented to treat moderately to heavily oiled shoreline in danger of being repeatedly oiled while the wellhead was leaking (USNRT, 2010). Shoreline Cleanup Assessment Technique teams created general STRs for Stage I and Stage II responses according to whether habitat was sandy shoreline, man-made shoreline, or coastal marshes and mangroves (DWH UC, 2010a). After the Macondo well was capped, SCAT teams shifted to Stage III responses to treat oiled shoreline (Santer et al., 2011). Stage III guidelines were based on SCAT Core Group concerns and Taskforce Working Group recommendations for different habitats (DWH UC, 2010b). Site-specific STRs were also created with the goal of removing enough oil to enable natural attenuation (Santer et al., 2011).

Response methods were selected according to the intensity and form of oiling as well as potential treatment impacts (DWH UC, 2010b). Strategies were guided by concepts underpinning net environmental benefit analysis, where responders clearly recognize what can be achieved before treatment actions become unsafe, become impractical, provide no significant benefit, or become damaging to shoreline habitat (DWH UC, 2010b; Santer et al., 2011). For sand shorelines, which represent perhaps the simplest logistical conditions for shoreline treatment, responses largely involved removal, tilling, and sifting of contaminated sand by crews supplemented with industrial scale equipment like "Sand Sharks" (DWH UC, 2010b). Sand was also cleaned in treatment plants and returned to affected shorelines (DWH UC, 2010b). Coastal marsh habitat presents significantly more challenging conditions for treatment as a consequence of soil and biotic structural complexity (USNRT, 2010). Although oiling mostly occurred along peripheral edges, oil penetrated tens of meters into marsh interiors at some locations, where foundational vegetation was coated to heights ranging from a few centimeters to over one meter due to tidal flux (DWH UC, 2011b; Lin and Mendelssohn, 2012; Silliman et al., 2012; Zengel and Michel, 2013). Thick layers of oil were found trapped in dense stands of vegetation, underneath organic debris (e.g., wrack), and on soil surfaces (DWH UC, 2011b; Lin and Mendelssohn, 2012; Silliman et al., 2012; Zengel and Michel, 2013). Oil also grounded on to root surfaces, which can prevent oil from penetrating deeply into soils. Guidelines for STRs and NFT under the Stage III Shoreline Treatment Plan recognized that treatment of sensitive marsh environments could cause physical harm significantly more detrimental than consequences solely attributable to oiling

(DWH UC, 2010b). The primary response recommended for oiled marshes was natural attenuation, whereby oil would be physically removed by wave action and tides or natural degradation through microbial metabolism and photooxidation (DWH UC, 2010b). Initial plans nonetheless identified a limited set of possible treatment options (depending on site conditions), which included low-pressure or ambient-temperature flushing, contained sorbents, manual removal, vacuuming, and vegetation cutting (DWH UC, 2010b).

Implementation of initial treatment options for coastal marshes proved problematic. Low-pressure, ambient-water flushing, which was permitted from vessels operated from the marsh edge, was not effective against heavy accumulations of fresh and weathered oil (DWH UC, 2010b). Low-pressure flushing techniques were also recommended for use only when tides covered marshes because spray turbulence could suspend sediment and spread contaminants (DWH UC, 2010b). This technique also saw little use because of limited availability in Louisiana; for example, only crews from St. Bernard Parish had access to proper equipment (DWH UC, 2010b). Contained sorbents, typically made of polypropylene, were used on water surfaces to recover oil being released from adjacent shoreline (DWH UC, 2010b). Limited surface area and the adsorbent nature of the boom provided little capacity for use against light sheens. Improperly monitored boom also became stranded in marshes, spreading contaminants, creating debris, and causing physical damage. Manual removal of oil was constrained by limited access and potential damage resulting from foot traffic; even light foot traffic can compact soils and cause significant long-term harm to resident biota in marshes. Consequently, manual oil removal was restricted to areas of marsh with firm sand or shell substrate, where hand tools such as trowels and shovels were used to remove thick accumulations (DWH UC, 2010b). Because of risks to sensitive shoreline, response teams typically only completed partial treatment through manual removal. Similar concerns restricted implementation of portable vacuum treatments to partial removal of oil from marsh shoreline: vacuums could not be operated from an offshore vessel without potentially disturbing and removing soil and sediment (DWH UC, 2010b). Cutting and removing oiled vegetation and organic debris, often with string trimmers and blades, was considered to be too aggressive to serve as a primary response approach. It was permitted on a case-by-case basis, however, for recovering oil trapped in thick stands of *Phragmites australis*. Initial treatment plans prohibited cutting *Spartina* cordgrass and mangrove vegetation (DWH UC, 2010b).

Several treatment methods were identified as being of little potential value because of limited applicability against weathered oil or because oiled materials could not be recovered from the environment. These included deluge flooding, solidifiers, loose sorbent materials, and surface cleaning agents (DWH UC, 2010b). *In situ* burning, where tidal flooding allows for plant regrowth by protecting roots from heat, would have been considered an appropriate remediation tool if the oil had been ignitable and floating freely in marshes (DWH UC, 2010b). Fertilizer additions to promote microbial metabolism and breakdown of oil were also ruled out because northern Gulf coast marshes are not nutrient-limited environments (DWH UC, 2010b). Methods specifically not recommended for vegetated shoreline included mechanical

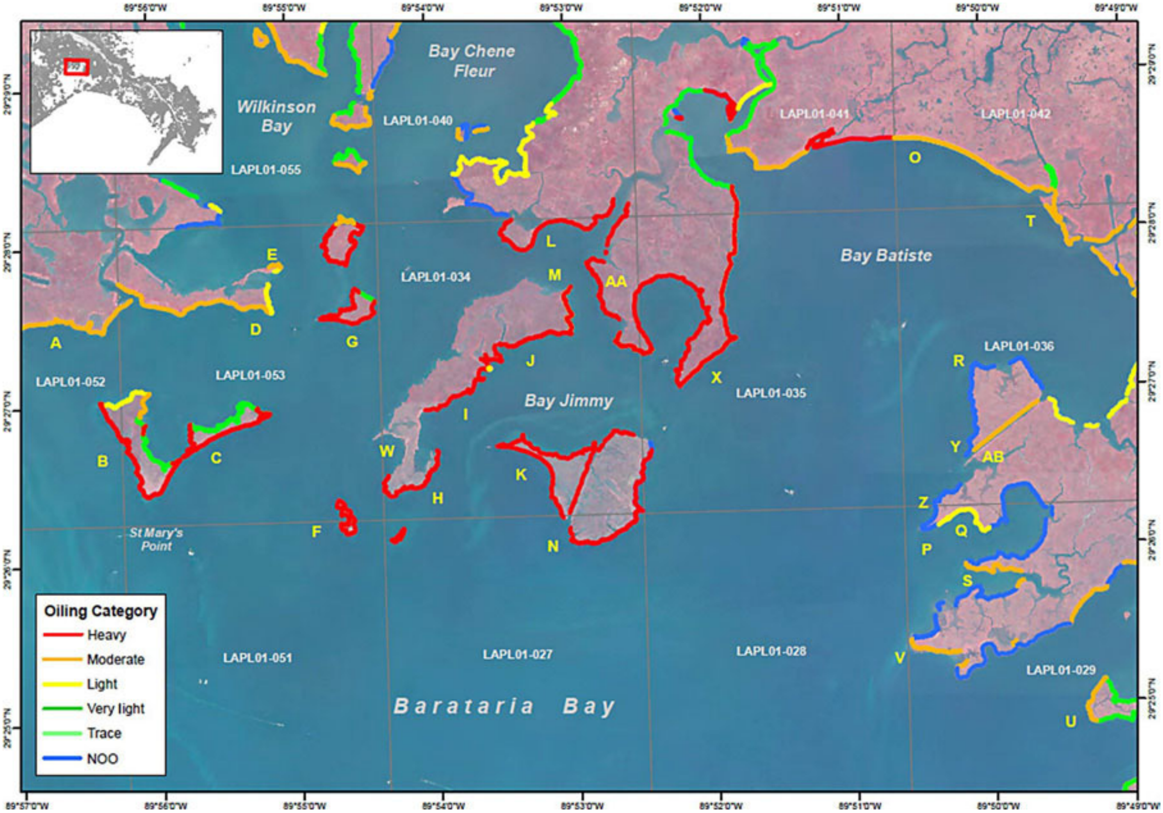

FIGURE 3.2 The distribution and intensity of oiling in northeastern Barataria Bay, Louisiana. Shoreline was categorized and identified for remediation according to the extent of oiling. Shoreline "K" in Bay Jimmy is host to ongoing studies of shoreline remediation and recovery. Map from Zengel and Michel (2013). *(See insert for color representation of the figure.)*

oil removal, sediment reworking/tilling, and any kind of high-pressure or heated water flushing (DWH UC, 2010b). These methods were deemed too destructive because of the likelihood that oil would penetrate further into porous sediment, that substrates would be compacted, or that plants or soil microorganisms would be damaged (DWH UC, 2010b).

The DWH Shoreline Treatment Implementation Framework incorporated guidance and recommendations to minimize potential harm from treatment approaches, citing research literature, agency protocols, and previous oil spill experiences compiled by the SCAT Taskforce Working Groups. The framework outlined appropriate Stage III STRs and NFT goals and was approved by Core Groups made up of stakeholder representatives. Nonetheless, SCAT teams developed STRs that strongly deviated from the Implementation Framework, and the UAC approved the use of aggressive strategies to remove oil from sensitive ecosystems.

The cleanup of marshes in Bay Jimmy (Barataria Bay, Plaquemines Parish, Louisiana), which may have received more oil than any other vegetated shoreline during the DWH event, offers exceptional examples of how cleanup crews implemented aggressive treatment strategies. Across Bay Jimmy (Fig. 3.2), vegetation laid down by waves became trapped under the weight of oil, creating tarry debris mats. Heavily oiled wrack lines subsequently hardened into tarry asphalt. Thick emulsified oil, or mousse, pooled on soil surfaces and became trapped beneath matted vegetation and wrack, preventing degradation. Tidal flushing and compaction nonetheless released buried mousse from exposed marsh. Few options are available to remove heavy accumulations of weathered oil without disrupting vegetated shorelines. The ineffectiveness of conventional treatment approaches, and the threat of additional resources suffering damages from oiling (i.e., contaminants could persist and potentially spread throughout the embayment), prompted consideration of aggressive tactics for remediation of Bay Jimmy shoreline. Following completion of a study to assess potential outcomes (as described in the following text), aggressive measures were implemented to recover oil trapped in marsh soils, vegetation, and debris that would have otherwise remained heavily contaminated (DWH UC, 2011b; Zengel and Michel, 2013).

In Northern Barataria Bay, 11 km of shoreline were treated using aggressive raking and cutting (Zengel and Michel, 2013). Cleanup crews entered marshes, provided that boards were laid down to serve as temporary walkways. Thick mousse was scooped out with shovels, and heavily oiled wrack lines and vegetation mats were raked and removed through manual or mechanical means (Fig. 3.3). Raking and cutting continued until contaminated soil and sediment were excavated, including horizons dominated by organic content. This continued until clean sediment was uncovered, often leaving only plant stubble behind (Zengel and Michel, 2013). When force was required to break through hardened surfaces to reach oiled mats below, tools like hedge trimmer and chain saws were used to penetrate surface tar and remove oiled debris (Zengel and Michel, 2013). A provision was made to allow heavy equipment to be used on a case-by-case basis to scale up treatment and improve response efficiency (Zengel and Michel, 2013). Long hydraulic arms operated from barges or airboats could reach into the marsh with automatic raking, cutting, and

FIGURE 3.3 Aggressive remediation of oiled shoreline in Bay Jimmy (Barataria Bay, Louisiana). Left: cleanup crews manually cutting oiled vegetation (Zengel and Michel, 2013). Right: mechanical removal of oiled material.

excavation attachments, allowing crews to scale up aggressive treatment techniques, but with less precision than manual remediation and increased potential to damage marsh soils. Heavy machinery also enabled debris to be transferred directly from the marsh to offshore disposal containers.

Seasonal conditions prompted shoreline treatment to be expedited (Zengel and Michel, 2013). Access generally improves toward winter months as tides decrease and substrates harden, and removing oil during winter also enables plants to recover the following spring before the beginning of hurricane season. However, shoreline treatment in Bay Jimmy stretched into the summer of 2011, when wet conditions in the marshes increased susceptibility to damage. Nonetheless, the approaching hurricane season raised concerns that unrecovered oil could become resuspended and redistributed, and spurred ambitious STRs for Northern Barataria Bay that prescribed aggressive removal approaches. By the end of September 2011, shoreline remediation crews had manually or mechanically removed over one million pounds of material from Bay Jimmy marshes alone (Zengel and Michel, 2013).

Remediation of vegetated shoreline was further complicated by the nature of on-site reviews of treatment outcomes. Meeting NFT guidelines under the STR for each site requires unanimous agreement between a federal representative (usually NOAA, a NOAA contractor, or USCG), a state representative, and a BP representative on each SCAT team (a landowner might also be involved) (Santer et al., 2011). Representatives sometimes disagree, though, as to what constitutes cleaned shoreline. Variable experience and training can contribute to differing perspectives, including the amount of emphasis placed on risks posed by toxicity and exposure.

Attempts to achieve consensus potentially pushed teams (i.e., particularly those that included determined members) to err on the side of overtreatment, extending well beyond STR guidelines. Yielding to aggressive removal techniques to obtain an immediate measure of remediation arguably reflects the difficulty of quantifying potential impacts of remaining debris or impacts arising from treatment.

3.3 ADVANCEMENT THROUGH FAILURE AND INNOVATION

The 1989 EVOS in Prince William Sound (Alaska) exposed troubling limitations in response technologies and approaches, including the design and implementation of chemical dispersants and shoreline cleaning agents. The EVOS resulted in passage of the Oil Pollution Act (OPA) in 1990, which created an interagency committee responsible for coordinating oil spill response research and technology development. Adopting the principles established by the OPA, some states (including California and Alaska) now explicitly require that oil spill response make use of the best available or "achievable" technologies. Under the OPA, spill response is intended to keep pace with advances in oil and gas exploration through a system of exercise drills, specialized training, and contingency planning (USEPA, 2011). Yet, response improvements have largely been motivated during oil spill events rather than from preparation between spills (Epperson, 2011). The logic of this is simple—interim preparation and planning based on past spill events and potential contingencies will not necessarily reflect novel conditions emerging from unfolding events. Little innovation will come from practice exercises and spill response training limited to a predetermined range of spill scenarios. The frequency and scope of exercises may also reduce the likelihood that innovations to improve deficiencies will emerge from planning and exercises (Epperson, 2011). In any given area of concern, exercises are held once every 3 years and may only involve participation of one "responsible party" (Epperson, 2011), which can prevent interactions among regulatory and industry partners (i.e., a port may have anywhere from 25 to 250 regulated entities) and limit knowledge of ACP. Furthermore, few clear mechanisms exist after exercises for sharing lessons, best practices, or new knowledge (i.e., of corrective actions) gained by agencies and outside partners.

Given the structure of the OPA, it is not surprising that the best available response technologies and approaches did not adequately address the range of conditions that emerged during the DWH event. The experimental use of dispersants is among the most widely recognized outcomes of the limited range of innovations that were achieved prior to the spill. Lisa Jackson, the administrator of the USEPA, described the novel use of dispersants as "somewhat trial and error," with concerns ranging from the potential impact of the volume of dispersants applied, effectiveness of dispersants at depth in low temperatures and high pressure, oil weathering as it rose to the surface, and environmental effects of dispersant in deep-ocean environments. Indeed, the Region 6 RRT Regional Integrated Contingency Plan lists one of the disadvantages of subsurface dispersant use as "lots of unknowns" (USEPA, 2011).

3.3.1 Evaluation of Alternative Response Technologies

Recognizing the need for innovation, the Unified Command implemented the NOAA-led alternative response technology evaluation system (ARTES) as response efforts proceeded during the DWH event. ARTES was developed to help identify viable spill-specific response tools through the evaluation of tools based on technical merit. Traditionally, ARTES only considers chemical and biological countermeasures, but the program was expanded during the DWH event to include mechanical countermeasures. The ARTES program consequently considered a range of technologies including oil sensors, booms, skimmers, decontamination and waste minimization technology, shoreline cleaning machines, and source containment innovations (Addassi, 2010).

The ARTES was modified during the DWH event to include four primary stages of review. There were four mechanisms for vendors wishing to introduce alternative technologies for use during the spill—Unified Command center walk-ins, website submission (www.horizonedocs.com), community meeting forums, and VIP submissions. VIP submissions were prompted by requests from high-ranking government officials or high-profile individuals or because the candidate technology garnered mass media attention during the course of the spill. Technologies that passed Stage III review were considered for field testing and potential adoption. Of the approximately 123,000 submissions, approximately 100 reached Stage IV field testing, and only 25 technologies were adopted (Addassi et al., 2011). Several of the field tested technologies originated as VIP submissions. These included the following.

3.3.1.1 Human Hair Sorbent Boom

Alternative sorbent technologies, including human hair, were considered for oil adsorption as a consequence of public pressure arising from extensive media exposure of a grassroots effort orchestrated by the nonprofit organization Matter of Trust (www.matteroftrust.org) to introduce the use of natural fiber as a filler material for sorbent boom. Media attention, which included interviews with the director of Matter of Trust by National Public Radio and the British Broadcasting Corporation, resulted in the donation of more than a dozen >10,000 square foot warehouses for storage and fabrication of hair booms across the Gulf coast. Hundreds of pounds of hair were received daily during the height of media coverage, with volunteers working to fabricate sorbent boom. Field tests of the boom, carried out by BP near the Incident Command Center in Mobile, Alabama, revealed that it did not float and therefore did not meet established criteria for sorbent boom.

3.3.1.2 A Whale Skimmer

A Taiwanese-made 1115 foot freighter, built originally as an oil/bulk/ore (OBO) carrier, was modified during the DWH event for oil skimming (Froomkin, 2010). According to maritime reports, the ship was in Rio de Janeiro awaiting orders when it then traveled 4240 nautical miles to a shipyard in Setubal, Portugal, for skimming modification. A series of twelve 16 foot slots were cut in the forward hull of the ship, allowing oil–water mixtures to pass into existing internal tanks where oil would separate from water by gravity. The water would then be returned to the ocean, and the oil would be held on the vessel for transport to a shoreside facility. On July 3, 2010, the BP, the USEPA, and the USCG conducted a test of the vessel's oil skimming ability. The USCG subsequently reported that *A Whale* recovered negligible amounts of oil. Limited to speeds of 2–3 knots, *A Whale* did not efficiently capture oil–water mixtures through its passive intake system (Rioux, 2010). Smaller Vessels of Opportunity were comparably more efficient and considered to be logistically more nimble than the modified freighter.

3.3.1.3 Costner Centrifuge

Blue Planet Water Solutions (BPWS) is a recently formed company founded by actor–director–producer Kevin Costner in collaboration with partners based in New Orleans. The mission of BPWS is to develop advanced oil–water separation technologies for oil spill cleanup. The company's foundation oil separation technology, which was transferred from the Department of Energy to Costner Industries Nevada Corporation (CINC) in 1993, is capable of highly efficient mechanical separation across a range of throughput conditions on board spill response vessels. The BPWS liquid–liquid centrifugal separator unit utilizes the force generated from rotating an object around a central axis. Spinning two fluids of different densities within a rotating container results in the heavier fluid being forced to the exterior walls of the rotor and the lighter fluid being forced to the center. Separation of oil and water can yield water of more than 99.999% purity and oil of more than 99.5% purity, depending on the nature of the crude oil, extent of weathering after the spill, receiving water chemistry, and state of oil emulsification.

With the assistance of Plaquemines Parish President Billy Nungesser, BPWS approached BP about carrying out field tests to evaluate potential applications of the company's centrifugal separation technology. The BPWS Integrated System was tested by BP in April 2010, after which engineers from BP and BPWS worked in concert to optimize the BPWS Integrated System to process recovered oil of various ages and in varying states of emulsification. After roughly a month of ongoing testing and optimization, BP leased 32 of the BPWS Integrated Systems, 8 of which were installed on *Edison Chouest Offshore* platform supply vessels (Fig. 3.4). In addition, two shallow-water barges from D&L Salvage and two deepwater barges from *Hornbeck Offshore Services* were outfitted with the BPWS systems to enhance onboard storage capacity via rapid dewatering of skimmed oil (Fig. 3.4).

During the course of the spill response phase, BPWS and its engineering partners integrated centrifugal oil dewatering with membrane-based water filtration technology.

FIGURE 3.4 Two BPWS Integrated Systems installed on the D&L Salvage spud barge *The Splash* (left) and four BPWS Integrated Systems installed on *Edison Chouest* platform supply vessel *ELLA G* (right).

The "centrifuge plus membrane" approach proved capable of rapid dewatering of skimmed oil followed by purification of effluent water to nondetectable levels of crude oil hydrocarbons. In comparison, the use of nonmembrane-based water filtration technologies (e.g., nutshell, coalescer, or organoclay media) did not significantly reduce crude oil hydrocarbon levels below that achieved by the centrifuge alone. Blue Planet Water Solutions and its engineering partner Water Planet Engineering (WPE) have subsequently designed a new centrifuge and membrane-based sediment–oil–water separator to handle small and large volumes of oil and water at throughputs of up to 400 gallons per minute within a footprint of a standard shipping container. The separator system, which is now referred to as the "*WPE Vorti-SEP™ Advanced Sediment-Oil–Water Separator* designed for BPWS by WPE," can handle changes in liquid ratios from 10:1 oil-in-water to 10:1 water-in-oil mixtures with similar efficiencies. Performance also can be adapted (in real time) to fluctuations in oil rheology, emulsification, flow rate, water quality, and temperature.

The BPWS *WPE Vorti-SEP* system is arguably among the best available oil spill response technologies. The use of technologies like the BPWS system can help to reduce use of conventional technologies and approaches—including chemical dispersants, burning boomed oil, and the use of oil adsorbent media—that can leave troubling environmental footprints. The BPWS system serves as an exceptional example of how the development and adoption of innovative treatment technology can increase the efficiency of oil spill recovery operations (e.g., improving the quantity and quality of recovered oil) while also addressing environmental concerns such as reducing hazardous waste disposal and discharging skimmed water that meets or exceeds clean water standards.

Ensuring that future spill responses make use of the "best available technology" requires that incentives to innovate and technology review programs be maintained on a permanent basis. A collaborative effort between federal and state agencies is now underway to revise the structure of ARTES so that it is available between oil spill events, with the goal of continuously improving spill response technologies. Nonetheless, it remains unclear whether sufficient incentives (e.g., grant programs, tax subsidies, industry safety regulations) will be emerge so that innovation and advancement of spill technologies does not wane.

3.3.2 Shoreline Interventions

Actions taken to keep oil from grounding on northern Gulf coast shorelines extended well beyond technology review and approval through the ARTES program. The demand for novel approaches and solutions to reduce risks of shoreline contamination increased with the growing magnitude of the DWH spill. Media and institutional pressure, sometimes from state and regional authorities, to protect shorelines resulted in major interventions being proposed and executed. The construction of temporary sand berms, restriction of tidal inlets, and diversion of Mississippi River flows were three highly controversial (i.e., of high risk and uncertain outcome) interventions executed to reduce the likelihood of oil entering sensitive coastal ecosystems.

3.3.2.1 Barrier Sand Berms

One month after the DWH rig exploded, the Louisiana Office of Coastal Protection and Restoration (OCPR) applied for a permit to build sand berm barriers to protect shorelines to the east and west of the Mississippi River outlet. The purpose of the project was to move 20 million cubic yards of dredge sediment seaward to the existing barrier island system in an effort to mitigate flow of oily seawater into the Mississippi Delta region. The OCPR application argued that the berm structures could function as geomorphic obstructions capable of protecting sensitive coastal ecosystems far more difficult to remediate than sandy substrate. The Louisiana Barrier Berm Oil Spill Response Project was approved by the Army Corps of Engineers on May 27, 2010 (USACE, 2010), with the USCG instructing BP to provide $360 million for construction of 74 km of sand berms on the Chandeleur Islands and from Scofield Island to Timbalier Island as part of the ongoing oil spill response. By November 22, 2010, however, only 20 km of berm had been completed according to the permitted plan.

Critics of the project—which was largely designed by a dredging company prior to the DWH event to help reduce saltwater intrusion into the delta—expressed concerns reflecting value, logistics, and functional outcomes. At least 1 million m^3 of material would be necessary to build 74 km of berms at the proposed 2 m height (Bahr, 2010). Suitable materials are limited in the areas where the berms were to be constructed (Finkl et al., 2006; Kulp et al., 2005), and much of the material in the areas of concern had already been identified for future barrier island restoration projects. Dredging of material in the targeted areas also could have resulted in displacement or mortality of benthic biota. By reducing seafloor elevations, for example, dredging can potentially reduce areas used by benthic biota as refugia during seasonal periods of anoxia (Erftemeijer and Lewis, 2006; Wilber and Clarke, 2001). Critics also argued against dedicating large amounts of response resources to temporary structures that might not function as expected (Martinez et al., 2011). Sand berms are immediately susceptible to erosion from wave action, especially during hurricane season. Assimilation of the berms into the littoral budget of the protected islands was presented as a potentially positive outcome of the project (Martinez et al., 2011), but critics viewed this as a suboptimal and costly use of limited resources. Noting many of these concerns, the National Commission on the DWH Oil Spill and Offshore Drilling (2011) concluded that the berm project was arguably "the most expensive and perhaps most controversial response measure deployed to fight the Deepwater Horizon spill."

3.3.2.2 Inlet Restrictions

During the DWH event, inlets located between barrier islands or at the mouth of estuaries functioned as potential gateways for oil to cross into inland waterways and ground on to interior shorelines. Recognizing the potential for oil to pass through inlets, state and parish authorities in Louisiana proposed closing the mouth of Barataria Bay with rock and barges. Coastal scientists expressed concern in response to the proposal, indicating that the project could have lasting detrimental consequences. By reducing tidal-driven sediment and water exchange, restriction of inlets can profoundly alter the physicochemistry of inland waters and ecosystems (Goodwin, 1996; Kraus and Militello, 1999; Martinez et al., 2011). Changes in salinity, oxygen levels, and turbidity of inland waters (Chaibi and Sedrati, 2009) can subsequently result in mass mortality of inland biota (e.g., fish kills). By increasing tidal flow velocity, inlet restriction also can promote scouring and loss of adjacent shoreline (Martinez et al., 2011). Although the permit request for the planned inlet closures for Barataria Bay was denied by the USACE, a similarly minded plan was executed on Dauphin Island at the mouth of Mobile Bay in Alabama. Referred to as the "Katrina Cut" project, geotextile tubes and riprap fill were used to close a gap in the island created by storm surge from Hurricane Katrina in 2005. The Katrina Gap closure was initially intended to be temporary, but it is now likely that the inlet will remain closed (Martinez et al., 2011).

3.3.2.3 Freshwater Diversions

Soon after the oil spill commenced, the State of Louisiana opened two diversions (with maximum discharge rates of 150–200 m^3/s) to allow freshwater from the Mississippi River to flow into Barataria Bay and Breton Sound. Diversions had previously been carried out to regulate salinity conditions and to deliver sediment for coastal restoration, whereas the intended outcome of the diversions during the DWH event was a countervailing force capable of preventing the flow of oil into inland waters and coastal ecosystems. No evidence is available that suggests the freshwater diversions prevented or reduced the flow of oil into inland waters and ecosystems (Martinez et al., 2011). It is becoming clear, however, that the diversions resulted in water quality conditions unfavorable to some of the coastal ecosystems, such as oyster reefs, slated for protection. The productivity of oyster grounds exposed to elevated freshwater conditions is expected to be depressed for a subsequent period of at least 3 years (Greater New Orleans Inc. Regional Economic Alliance, 2010).

Although the decisions to construct sand berms, fill inlets, and divert freshwater may indicate otherwise, innovation in spill response will likely be a defining element of the DWH legacy. The costly and controversial interventions undertaken during the DWH event underscore the importance of basing spill response strategies on sound scientific knowledge so that outcomes do not undermine long-term coastal management plans. Perhaps even more so than the EVOS, the DWH spill has promoted greater awareness and appreciation that logistical and technological challenges must be overcome while being mindful of ecological conditions to effectively recover and sustain valued ecosystem services provided by oiled shoreline habitats.

A growing body of research begun soon after the Macondo well blowout will undoubtedly help advance oil spill response in the GoM and elsewhere. RAPID grant funding from the National Science Foundation (NSF), for example, provided support for a suite of studies on GoM marine and coastal ecosystems. Although the policy of NSF RAPID funding is to provide time-sensitive support for basic science, many of these studies were intended to assess outcomes of oil being released into the Gulf. Studies intended to evaluate the influence of oil on the structure of salt marsh and estuarine food webs, for example, can also provide a basis for assessing whether species interactions and trophic cascades extend the footprint of exposure beyond immediate contact (Graham et al., 2010). Other studies intended to evaluate biogeochemical outcomes of carbon subsidies from oil degradation can help determine the potential for manipulating resources (e.g., nutrients) to optimize plant and microbial breakdown of oil under recalcitrant conditions. The legacy of advancement will be considerably extended through funding made available by BP for applied research on oil spill dynamics and outcomes. Managed by the Gulf of Mexico Research Initiative (GoMRI), this 10-year $500 million program aims to build comprehensive knowledge of oil spills. The program will undoubtedly offer stronger platforms for innovation in oil spill response, including improved methods for shoreline remediation.

3.3.3 Proving Grounds for Shoreline Remediation and Restoration

Bay Jimmy has become a proving ground for determining how to advance the process and outcomes of shoreline remediation, with the goal of identifying clear pathways toward recovery. Remediating oil from coastal marshes presents technical (i.e., what approach will remove the greatest amount of oil while doing the least harm?) and logistical (i.e., when and how rapidly should oil be removed?) challenges that can involve trade-offs. Without greater understanding of potential outcomes of alternative treatment approaches, decisions to escalate remediation to meet immediate demands could jeopardize long-term ecosystem recovery. It is possible, for example, that reducing environmental exposures to oil may come at the expense of marsh integrity. Wholesale removal of soil, organic debris, and plant cover during treatment also can endanger marshes by reducing elevation via loss of above- and belowground biomass and subsidence through elevated metabolism of subsurface organic soils following exposure to oxygen (Hatton et al., 1983; Nyman et al., 1993, 2006; Turner et al., 2006; Walker et al., 1987). Aggressive remediation that increases inundation and erosion can result in greater rates of marsh loss and conversion of shorelines to open water, especially in areas like Barataria Bay where background rates of loss are among the highest on the Gulf coast (USGAO, 2007). Alternative approaches that leave oil in marshes may not immediately eliminate risks of chronic exposure and toxicity, but marsh platforms remain largely intact as risks of exposure decline over time due to natural attenuation, burial, and weathering.

Recognizing that marsh habitat is difficult to regain once it is lost, the Unified Incident Command approved a plan for conducting tests in Northern Barataria Bay to evaluate outcomes of aggressive treatment approaches. Led by Dr. Scott Zengel, a scientist overseeing shoreline assessment for NOAA, a remediation treatment study was implemented to improve decision-making for ongoing marsh cleanup efforts (Zengel and Michel, 2013). The study was designed to evaluate three primary treatments (vegetation cutting, vegetation raking, and vegetation raking followed by cutting), followed by four secondary treatment techniques (low-pressure flushing, two types of surface washing agents, and vacuuming). Comparisons were drawn to areas that received no treatment (i.e., areas set aside to undergo natural recovery) and uncontaminated areas that served as controls. On shoreline "K" of Bay Jimmy (Fig. 3.2), treatments were randomly assigned across plots measuring 8.5 m along the water's edge and 10 m toward the marsh interior, including the oiled wrack line bounding landward contamination. Unexposed control sites were located on nearby shorelines. Treatments were applied adaptively, allowing ineffective techniques to be discarded as tests proceeded. For example, vegetation cutting using a weed trimmer was immediately abandoned after various cutting attachments failed to remove oil mats, even after plots underwent preparatory raking. Instead, raking was used to break up oiled mats until the mousse below was exposed to weathering.

Early observations revealed no difference in oil characterization following the initial treatment tests. Vegetation left standing had subsequently laid down, trapping oil beneath a new tarry mat. Subsequent tests employed more aggressive techniques, including raking down through the oil and cutting vegetation with articulating hedge trimmers on poles. Mousse was raked onto standing vegetation, allowing it to be cut out and removed with exposed plant growth. Raking and cutting were alternated until only clean sediment remained. Responders gathered oiled debris for disposal and then proceeded to test secondary treatment options. Low-pressure washing and each of two surface washing agents (CytoSol and PES-51, both NCP Product Schedule listed) were tested in three different plots. These treatments resulted in scouring upon application and failed to release oil from the marsh beyond sheening. Vacuuming from marsh boards resulted in the recovery of more water and sediment than oil and also promoted subsurface penetration of oil. Further tests of secondary treatment techniques were consequently canceled.

Conditions in the treatment and control plots were monitored on a monthly basis from October 2010 through September 2011 following SCAT protocols to characterize oil, sediment chemistry, vegetation cover, and benthic macroinvertebrates. SCAT assessments measure oiling distribution (length, width, percent cover), oiling type (oiled wrack, oiled vegetation/debris mats, oil on standing vegetation, oil on/in substrate), oil thickness, and oil character (liquid oil, mousse, surface residue, tar, etc.). Cross sections from dominant oiling zones also are used to quantify oil burial, penetration, and mixing into subsurface sediments.

Preliminary findings of the remediation study indicated that aggressive treatment enabled effective recovery of oil without jeopardizing marsh integrity. Aggressive raking and cutting were the only treatment that completely and persistently removed oiled vegetation mats and that left no evidence of increasing oil penetration or mixing in subsurface sediments. Vegetation regrowth appeared to be greater in aggressively treated plots than other treatment plots, which in turn experienced greater regrowth than plots undergoing natural recovery. Preliminary surface sediment chemistry data, however, indicated that total petroleum hydrocarbons and polycyclic aromatic hydrocarbon content did not differ across the treatments, though levels were slightly lower and more weathered in aggressively treated plots.

The treatment study implemented in Bay Jimmy represents an innovative effort to provide standardized, replicated comparisons of treatment options to inform ongoing remediation efforts. Follow-on studies are nonetheless necessary to provide more rigorous understanding of postremediation shoreline recovery. Coastal marsh responses to disturbance can span years to decades. Plant responses, soil oxidation, rates of decomposition, and consequences of compaction, subsidence, and erosion are all important ecosystem characteristics that have not yet been assessed. Continued monitoring of the treatment plots represents a singular opportunity to track ecosystem recovery following alternative shoreline remediation approaches. Yet, it is unclear whether the treatment plots will remain available for study. Completion of Stage III response requires that all oiled shoreline receive treatment to satisfy NFT guidelines. Petitions have been filed to exempt the study plots from treatment, highlighting how useful continued research would be for future oil spill responses.

Bay Jimmy has also become a proving ground for achieving better integration of remediation and restoration. Undertaking restoration alongside remediation—something that could be referred to as "restorative remediation"—could enhance treatment and recovery of sensitive ecosystems such as coastal marshes in erosional environments (Bergen et al., 2000). Under the current plan, restoration is not part of the NCP and NIMS. Barring a settlement, restoration follows completion of the NRDA process: after data is gathered to determine resource injury, economic and scientific studies are conducted, a restoration plan is developed, and trustees identify restoration projects of interest (NOAA, 2012). Consequently, years can pass between shoreline remediation and restoration. Long delays between remediation and restoration elevate risks of habitat loss and consequent losses in dependent species and valued ecosystem services (Bergen et al., 2000), especially for erosional environments like Bay Jimmy. Restorative remediation (as compared to emergency restoration or restoration following the NRDA process) can potentially reduce responsible party costs and long-term natural resource damages. Restorative remediation might also reduce costs by eliminating redundant logistical expenses, as restoration could be readily implemented via response personnel and equipment marshaled for shoreline treatment. Denuded shorelines in Bay Jimmy, for example, could have been anchored with plants to replace lost vegetation after remediation crews removed oiled material. Although concerns about rates of survivorship of transplants in oiled sediments must be addressed (Bergen et al., 2000), integrating restoration with remediation could alleviate concerns of loss while making better use of available resources.

Studies are being carried out in Bay Jimmy to assess the outcome of alternative restoration approaches in areas where remediation has left behind exposed shoreline at risk of inundation and erosion. A series of test plots were established in July 2011 through academic–industry–agency partnerships (led by Tulane University, WPE, and BPWS) to evaluate the recovery of exposed shorelines planted with native and cultivated smooth cordgrass (*Spartina alterniflora*) genotypes. Smooth cordgrass functions as an "ecosystem engineer" by regulating physical and biological conditions independently of the local environment (Seliskar et al., 2002). The addition of smooth cordgrass to remediated shoreline can prevent marsh loss by trapping mineral sediment, adding organic biomass to substrates, and armoring platforms against tidal erosion. Replanting shorelines may also encourage oil degradation by oxygenating soils, elevating microbial metabolism in soils, and uptake of hydrocarbons from soils (Lytle and Lytle, 1987; Pezeshki et al., 2000; Sandmann and Loos, 1984; Walton and Anderson, 1990). Different smooth cordgrass genotypes, however, exhibit variation in functional performance. Properties known to vary according to *S. alterniflora* genotype range from plant community composition (Proffitt et al., 2005), microbial activity and diversity (Nie et al., 2010; Seliskar et al., 2002), organic matter distribution, and the presence of fish larvae (Seliskar et al., 2002). Marsh restoration projects in Louisiana nonetheless are now required to use a single smooth cordgrass genotype, referred to as Vermilion, which has been cultivated for maximum aboveground biomass, disease resistance, and transplantation survival at the expense of other traits such as belowground biomass (Utomo et al., 2008). The use of cultivars for marsh restoration can alter local gene pools through replacement or admixture with native genotypes. By extension, conventional restoration can result in unexpected and potentially undesirable ecosystem properties.

The test plots in Bay Jimmy have been planted with arrays of native genotypes, Vermilion, and other cultivar genotypes to first assess how planting contributes to the recovery of remediated shoreline and to also assess how use of different parent stocks can influence ecosystem attributes. For each plot, bare-root stems were hand-planted in four rows perpendicular to the shoreline, spaced on 1 m centers (Fig. 3.5). Planted rows began 5 m from the water's edge, with each row containing 11 stems spaced 0.5 m apart. Baseline characteristics of soil structure and content, surface and subsurface hydrocarbon content, and plant productivity were measured prior to planting. Plot characteristics have subsequently been monitored on a monthly basis, with additional information on accretion rates, soil stabilization, and soil development collected at quarterly intervals. By capturing regular and stochastic disturbances, such as storm events, the study will offer exceptional opportunities to assess shoreline resilience.

Improving restoration technologies to decrease the labor, expense, and risk associated with planting marsh vegetation could further promote recovery of remediated shorelines. Because smooth cordgrass exhibits low seed viability, restoration projects often involve manual installation of plants. Using stems, plugs, or containers costs an average of $9000 per acre in Louisiana CWPPRA projects and requires labor ranging from 25 to 125 h/acre (Leonards, 2008; USGAO, 2007). Besides the costs involved, logistical challenges of manual installation limit the feasibility of large-scale implementation. Salt marshes are often remote environments that are difficult to access. Also, marsh substrates are fragile, so entry and movement within a marsh can result in considerable damage.

Members of the academic–industry–agency partnership are undertaking additional transplant studies in Bay Jimmy to test prefabricated technologies that aim to address some of these concerns. Biodegradable mesh tubes have been designed and built to

FIGURE 3.5 Shoreline restoration studies being conducted in Bay Jimmy; transplant plot (left), propagation tube plot (center), and detail of propagation tube (right).

contain smooth cordgrass rootstock in a bagasse growth medium (Fig. 3.5). Bagasse is a waste product left over from refining sugarcane that is readily available from the Louisiana sugarcane industry. Diverted from processing plants, it can be supplemented with organic substrate to create a mixture that facilitates plant establishment. This design enables plants to be introduced to targeted restoration sites by simply laying out and securing “propagation tubes” on exposed shoreline. Incorporation of plants into the design allows natural root growth to help anchor tubes securely to the marsh. The tubes therefore promote regrowth while armoring shorelines against erosion.

During experimental trials conducted in Bay Jimmy, tubes were established in plots measuring 15 m wide along the shore and 15 m long from shore. The propagation tubes were initially arranged as a comb with four tubes perpendicular to the shoreline (spaced 1 m apart) abutting a fifth tube that was placed on top of the shoreline scarp. The tubes were secured with wooden furring strips at 1 m intervals. This arrangement proved unstable, however, during storm events. In subsequent trials, the comb arrangement faced the water, which minimized stress from wave impacts (Fig. 3.5). This configuration also caused the interior tube to trap debris carried to shore, resulting in the rapid development of organic wrack. Other preliminary observations indicated that the propagation tubes reduce marsh restoration labor and expense while increasing the pace of shoreline development and facilitating lateral growth of the marsh surface. Smooth cordgrass root masses in deployed tubes exhibited nearly 100% survivorship, and the slow deterioration of the tubes appears to be enabling plants to become firmly embedded in the marsh platform as root expansion take place. Further monitoring and additional trials will be necessary to quantify rates of regrowth, shoreline development, and marsh accretion (Bergen et al., 2000).

3.4 CONCLUSIONS

The Macondo well blowout resulted in an environmental disaster of global proportions. In an era of energy production shifting away from coastlines, it has redefined our understanding of risks associated with deepwater wells. It has enhanced our awareness of the intricate complexity of communities whose livelihoods rely as much on the energy sector as on fisheries that are at risk from well blowouts. The disaster has also refocused our attention on Gulf coast ecosystems, including at-risk areas of the Mississippi River Delta that sustain ecological and cultural resources of national importance.

Understanding of ecological and related economic outcomes of the DWH oil spill remains cursory, including potential timelines of recovery (i.e., return to a state comparable to states exhibited by uncontaminated sites). Based on commonly measured ecological parameters (e.g., vegetative cover and structure, species diversity, petroleum hydrocarbon concentrations in soils), recovery times for oiled marshes can range from a few weeks to decades. Recovery times spanning years to decades have been documented for marshes in cold-temperate environments that were heavily exposed to fuel oils such as bunker C or no. 2 fuel and that were damaged by intensive remediation methods (Hoff, 1995). Under recalcitrant conditions (Baker et al., 1993; Getter et al., 1984; Hambrick et al., 1980), oil persisting in buried sediments can continue to influence the integrity of coastal ecosystems long after a spill. Four decades after the 1969 *Florida* barge spill in Wild Harbor (Massachusetts), oil remaining in marsh sediments continued to stunt belowground growth, with affected areas exhibiting lower marsh elevations and greater bank erosion (Culbertson et al., 2008). Long recovery times were also found following a spill in Buzzards Bay, Massachusetts; the *Miguasha* spill in Canada; the *Metula* in Chile; and the *Amoco Cadiz* in France (Baca et al., 1987; Baker et al., 1993; Hampson and Moul, 1978; Vandermeulen and Jotcham, 1986). Recovery times of less than a year were found for marshes in warm climates that experienced light to moderate oiling with light crude oil and little or no remediation (Hoff, 1995). Several of the spills resulting in short recovery times have occurred in Galveston Bay and other areas of Texas (Hoff, 1995). Similar recovery rates might be expected following the DWH spill (i.e., evidence of natural recolonization and regrowth has been found in some oiled marshes), except that oil from the blown Macondo well grounded on to erosional shorelines and heavily degraded deltaic wetlands–hotspots of habitat loss. Aggressive remediation that strips marshes of plants and sediment could compound injury or fully prevent recovery, given the distinct possibility of accelerated habitat loss (Baca et al., 1987; Bergen et al., 2000; Lin and Mendelssohn, 2012; Mendelssohn et al., 2012; Silliman et al., 2012; Vandermeulen and Jotcham, 1986).

Redressing shoreline damage from the DWH event requires science-based approaches that address the trifecta of oiling, erosion, and subsidence. In the future, embracing a policy of shoreline remediation followed by habitat restoration can promote postspill recovery while preventing habitat loss from erosion or subsidence. Restoration should not be considered a consequent step to remediation, but rather an important remediation technology in its own right, imperative to protecting oiled shoreline from damage and loss. The potential for restoration to promote postspill recovery through revegetation or accelerating natural recolonization has been widely recognized (Baker 1971; Dicks and Levell, 1989; Krebs and Tanner, 1981; Webb and Alexander, 1991). Baker (1971), for example, suggested that faster recovery of marshes might be achieved by planting *Spartina* shoots directly into oil-laden sediments. This suggestion is supported by Lin and Mendelssohn (1998), who showed that *S. alterniflora* can successfully recolonize areas with oil concentrations as high as 250 mg/g so long as the oil is sufficiently weathered. Although little formal work has been done to assess postspill restoration outcomes, Bergen et al. (2000) found that replanting significantly improved marsh recovery after the 1990 *Arthur Kill* oil spill in New Jersey. Oiled salt marshes where smooth cordgrass was replanted exhibited 70% vegetative cover after 3 years, whereas only 5% coverage was achieved at oiled sites that were not replanted (Bergen et al., 2000). The treatment study and follow-on restoration studies in Bay Jimmy represent important steps toward achieving greater understanding for Gulf coast marshes.

Restoring oiled shorelines to conditions comparable to natural ecosystems is a deceptively simple goal. Conventional restoration practices often fail to recover original levels of ecosystem function and structure (Moreno-Mateos et al., 2012).

Understanding the ecological outcomes of practical trade-offs can help minimize undesirable outcomes. Some choices made during project execution, as simple as the spacing of transplanted propagules, can lead to failure. Other choices, such as replanting shorelines with ecosystem engineers (e.g., smooth cordgrass), can modify ecosystem attributes and result in alternative states that will never resemble reference conditions (Moreno-Mateos et al., 2012). Although conventional practices can serve as precautionary measures to ward off the specter of habitat loss, innovative methods for shoreline restoration may prove critical for the recovery of Gulf coast ecosystems.

Shoreline remediation and restoration should be guided by comprehensive coastal restoration plans. It has long been recognized that coastal ecosystems of the northern GoM, and in particular wetlands of the Mississippi River Delta, are in dire need of restoration. Vast areas of the Mississippi River Delta are being lost and will continue to disappear without restoration being undertaken at a grand scale. Many of the challenges of coastal restoration are well recognized and are being addressed in regional and statewide plans (e.g., CPRA, 2010) that have broad support from coastal scientists and stakeholders. These plans can serve as a secure platform for remediation and restoration of oiled shoreline. New challenges may surface, however, as information becomes available from ongoing studies of coastal ecosystem responses to oiling. Accordingly, greater reciprocity between oil spill response efforts and coastal restoration planning will help ensure that progressive measures are taken to secure the future of Gulf coastal ecosystems.

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