Prospects for Wetland Recovery in the Northern Gulf of Mexico

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The explosion of the BP oil rig Deepwater Horizon has resulted in the single largest oil spill recorded in the Gulf of Mexico.[1] As a result, there are immediate and long-term concerns regarding the environmental health of the northern Gulf of Mexico (GOM) region (the Florida Panhandle to Texas). In this region, tidal wetlands are largely salt marshes (non-forested wetlands), although there are also small and highly scattered populations of black mangroves (*Avicennia germinans*) along the coasts of Louisiana and Texas and tidal freshwater wetlands (marshes and forests) within coastal rivers and creeks.[2] Oil spills have the potential to impact all of these wetlands, but in terms of oil exposure and wetland area, the greatest impacts are expected to salt marshes.

An estimated one million hectares (ha) of salt marsh occurs along the GOM, with approximately 43% occurring in the Mississippi River Delta.[3] Salt marshes occur in the intertidal zone, where there is sufficient protection from wave energy often near river mouths, bays, and in protected lagoons. Being in the intertidal zone, they are subjected to daily tidal fluctuations and may alternate from drained to submerged on a daily basis. In the northern GOM, tides are usually small (<1 meter (m)), however, because of the flat topography along the coast, intertidal zones can be extensive. Salt marshes in the GOM are dominated by rooted perennial grasses and rushes, including: smooth cordgrass (*Spartina alterniflora*); salt meadow cordgrass (*Spartina patens*); salt grass (*Distichlis spicata*); and black needle-rush (*Juncus roemerianus*).[4] Few plant species are adapted to survive in these marshes because of highly anaerobic soils (caused by prolonged flooding) and the added stress of salinity. As a result, salt marshes are usually not species-diverse and often a single species will form nearly homogeneous stands. The range of tidal flooding and elevations within a marsh often promote discernable high- and low-marsh zones that can be occupied by different species or different growth forms of the same species.[5] In addition to tides and salinity, salt marsh vegetation is influenced by other factors, including substrate type (muds, sand, and peat), climate (temperature, rainfall, and hurricane patterns), freshwater flow, biological competition, and surrounding land use/human activities.[6] Despite the stressful environment, these marshes are often highly productive and complex ecosystems with multiple bottom-up and top-down factors that affect ecological processes.[7] Salt marshes are fragile habitats and extremely important breeding grounds for many species, including those considered economically important for fisheries, such as brown shrimp (*Farfantepanaeus aztecus*), white shrimp (*Litopenaeus setiferus*), blue crab (*Callinectes sapidus*), and several pelagic fish.[8] They also provide important habitat for species that make up the food base for other commercially important fish species and species of conservation interest, e.g., wading birds. Coastal marshes are also critical for shoreline protection and storm-surge abatement,[9] particularly with increasing human development along the U.S. coastline. In short, tidal marshes along the northern GOM are critically important ecosystems.

The potential impact and recovery to salt marshes caused by oil exposure is difficult to generalize, because of inherent differences between wetlands, the varying nature of oil impacts, and the range of potential cleanup options that could be employed. Predicting future conditions and recovery is probably premature, because the full extent of damage caused by this oil spill is still unknown. However, research and accounts from past oil spills provide important lessons for anticipating wetland impacts and selecting appropriate management tools for recovery. We review some of these lessons learned and identify factors that will likely determine the extent of wetland damage and recovery.

1. Cutler J. Cleveland, *Deepwater Horizon Oil Spill*, *in* The Encyclopedia of Earth (Cutler J. Cleveland ed., Environmental Information Coalition, National Council for Science and the Environment, 2010).
2. William J. Mitsch et al., Wetland Ecosystems 295 (John Wiley & Sons, Inc. 2009).
3. Ralph W. Tiner, Field Guide of Coastal Wetland Plants of the Southeastern United States (Univ. of Mass. Press 1993).
4. *Id.*
5. *See* Mitsch et al., *supra* note 2.
6. *See* Tiner, *supra* note 3.
7. Jenneke M. Visser & Donald M. Baltz. *Ecosystem Structure of Tidal Saline Marshes*, *in* Coastal Wetlands: An Integrated Ecosystem Approach 425-44 (G.M.R. Perillo et al. eds., Elsevier Science, 2009).
8. Lawrence P. Rozas et al., *An Assessment of Potential Oil Spill Damage to Salt Marsh Habitats and Fishery Resources in Galveston Bay, Texas*, 40 Marine Pollution Bull. 1148-60 (2000).
9. John D. Day Jr. et al., *Restoration of the Mississippi Delta: Lessons From Hurricanes Katrina and Rita*, 315 Science 1679-84 (2007).

I. Wetland Impacts Caused by Oil Exposure

Often, the immediate effect of oil on tidal marshes is the loss of marsh vegetation (plant senescence) soon after exposure. Reza Pezeshki and colleagues described three general effects that oil exposure has on marsh plants: physical effects; chemical effects; and the effects caused by oil penetrating into the wetland soil.[10] Physical impacts involve the coating of oil on plant and soil surfaces. When oil is coated on leaves and stems, it can block transpiration pathways (plant stomata), which leads to several negative (and related) effects to the plant, including: the disruption of plant-water relationships; reduced photosynthesis and plant metabolism; and reduced oxygen (O_2) exchange between the atmosphere and soil.[11] Oil-blocked transpiration pathways restrict carbon dioxide from entering plant tissue and, consequently, reduce photosynthesis. Restricted pathways also reduce plant transpiration, nutrient uptake, and the ability of plants to regulate internal temperatures. As a result, plants are often unable to function physiologically, and leaves and stems eventually begin to die off. Oil-coated wetland plants may also be restricted in the amount of O_2 that is transported to their root zone. Most wetland plants have adapted to living in flooded and anaerobic soils by developing leaf and stem tissue that supports the movement of atmospheric O_2 from leaves and stems to its roots and rhizomes. When transpiration pathways are blocked, this adaptation is impaired. Reduced O_2 to the root zone also reduces the activity of certain soil microbes that depend upon the O_2 diffused from roots and rhizomes and into the soil. This can be important, because aerobic microbes have a higher capacity to break down oil than anaerobic microbes.[12] A limited amount of O_2 can diffuse directly from the atmosphere into the wetland soils, particularly when soils are drained during low tides. However, when soil surfaces are coated with oil, this process also becomes limited, further reducing soil O_2 levels.

Initial exposure to oil can cause a dramatic die-off of marsh leaves, but plants often recover and begin regenerating new shoots later in the growing season. The disruption of photosynthesis, along with the inability to regulate internal and surrounding conditions, has been shown to lead to the death of *Spartina alterniflora* leaves within 40 days of exposure. However, as long as the plant rhizomes are intact, wetland plants can produce new leaves within two weeks.[13] The ability of plants to regenerate after oil exposure is dependent upon the store of carbohydrates in below-ground rhizomes. Plants essentially draw upon this energy reserve to grow new leaves and are capable of regenerating multiple times. However, over time, if plants repeatedly lose leaves from oil exposure, they may eventually deplete the carbohydrates stored in rhizomes resulting in the fatality of the entire plant. With the complete death of plants, there is the potential for more permanent loss of marshes. Areas where entire plants have died off become susceptible to soil displacement and subsidence, contributing to a more permanent loss of marsh habitat.

A. Variation in Wetlands

There are various site-specific factors to be considered when predicting how oil will impact wetlands. Salt marshes can be dominated by different species with different susceptibilities to oil. *Spartina alterniflora* is the most common species in the Mississippi Delta marshes where oil exposure has been the heaviest so far, while *Juncus roemerianus* is the dominant plant in other regions of the northern GOM.[14] Both species can occur as nearly pure stands. Pezeshki and Ronald DeLaune showed that both *Spartina alterniflora* and *Juncus roemerianus* responded to partial oiling with a reduction in photosynthesis over several weeks, but with no lethal effects.[15] *Spartina patens*, another common marsh grass along the GOM, has shown to be more sensitive to oil than *Spartina alterniflora* and less capable of recovering after exposure.[16] DeLaune and his colleagues investigated the effect of oil on species common to coastal marshes using a combination of greenhouse and field studies.[17] From their field study, *Spartina alterniflora*, *Spartina patens*, and *Sagittaria lancifolia* all recovered after an experimental field application of south Louisiana crude oil (2 liters m^{-2}). Above-ground plant material of each species died after application, but then regenerated thereafter, although *Spartina patens* responded the slowest.

B. Oil Type and Exposure

Chemical impacts of oil on marsh plants involve toxicity to living cells and vary depending upon the type of oil and amount of exposure. Oils are generally classified into five different types: (1) very light oils, like automotive gasoline and jet fuel; (2) light oils, like diesel fuel, No. 2 fuel oil, and light crude oil; (3) medium oils, such as most crude oils; (4) heavy

10. S. Reza Pezeshki et al., *The Effects of Oil Spill and Clean-Up on Dominant U.S. Gulf Coast Marsh Macrophytes: A Review*, 108 Envtl. Pollution 129-39 (2000).
11. *Id.*
12. Ronald D. DeLaune et al., *Fate of Petroleum Hydrocarbons and Toxic Organics in Louisiana Coastal Environments*, 13 Estuaries 72-80 (1990); Jae-Young Ko & John W. Day, *A Review of Ecological Impacts of Oil and Gas Development on the Coastal Ecosystems in the Mississippi Delta*, 47 Ocean & Coastal Mgmt. 597-623 (2004).
13. *See* Pezeshki et al., *supra* note 10.
14. *See* Tiner, *supra* note 3.
15. S. Reza Pezeshki & Ronald D. DeLaune, *Effects of Crude Oil on Gas Exchange Functions of* Juncus roemerianus *and* Spartina alterniflora, 68 Water, Air & Soil Pollution 461-68 (1993).
16. Irving A. Mendelssohn et al., Effects of Oil Spill on Coastal Wetlands and Their Recovery, OCS Study 46, MMS 93-0045, U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office (1993).
17. Ronald D. DeLaune et al., *Sensitivity of U.S. Gulf of Mexico Coastal Marsh Vegetation to Crude Oil: Comparison of Greenhouse and Field Responses*, 37 Aquatic Ecology 351-60 (2003).

oils, including heavy crude oil and No. 6 fuel oil; and (5) very heavy oils that do not float on water, like some heavy No. 6 oils.[18] Samples of oil spilling from the Deepwater Horizon site have been identified as a heavier oil that emulsifies well,[19] but lighter crude—more typical to the GOM—has been detected as well.[20] Unlike most of the oil drilled in the GOM, such as Louisiana light sweet crude or BP 2010, the heavier blend is geologically older material that is normally found in deeper waters. The oil tends to emulsify, meaning that it readily mixes with water and can form tar balls—the gooey mousse-like consistency already observed along the GOM shoreline.

The type of oil and crude weight exposed to coastal wetlands will have ramifications for impact and recovery. While it appears marsh plants can tolerate crude oil exposure, refined oil exposure or high crude oil concentrations in the soil can destroy marsh habitats.[21] Diesel, No. 2 oil, and certain refined, light oils have been shown to be more capable of penetrating plant tissue and reducing plant regeneration.[22] In one experiment, No. 2 fuel oil significantly reduced aboveground growth of salt marsh grasses, while crude oil, applied at a higher rate, did not.[23] Vegetation reacts differently when coated with refined oils versus crude oils. For example, when *Spartina alterniflora* plants were exposed to Bunker C oil (refined heavy oil), they did not produce new leaves and later died.[24] When the same species of plants were completely contaminated with south Louisiana crude, all of the leaves rapidly died, but began to reemerge within two weeks. Two months later, they functioned much like the control plants for the experiment.[25] Other studies looking at crude oil exposure on the growth of *Spartina alterniflora* have found no negative effects.[26] Although more resistant to degradation, e.g., evaporation, breakdown, dissolution, oxidation, or biodegradation by microorganisms, heavier oil types may be less damaging to wetland plants, but the sticky consistency and resistance to degradation may enable them to persist in the environment over a longer time.[27]

Another consideration is the potential for long-term exposure to oil. If exposure is short-term and limited to plant surfaces, the prospect for wetland recovery is very good. More permanent effects may occur when oil exposure is chronic or if soils become fouled by oil. Soil fouling (see below) may occur in wetlands that are repeatedly exposed to oil or where oil is pushed into wetlands that are only flooded periodically (by an extremely high tide or storm event). In these circumstances, oil exposure may be long-lasting and detrimental to plants. Oil exposure can cause the fatality of below-ground organs and eventually the entire plant. Where this occurs across large areas, the decomposition of plant rhizomes may lead to soil subsidence and more permanent marsh loss.

The weathering of oil may also be an important factor. Unlike other spills, oil from the Deepwater Horizon spill site may travel hundreds of kilometers over several days before reaching the shoreline. During that time, oil may partially degrade, and dispersants designed to break down oil into smaller components may also promote further oil weathering. Weathered oil affects marshes differently and is generally accepted to be less toxic than fresh oil. In England, Prof. E.B. Cowell discovered marshes were more impacted by oil that made landfall within minutes rather than days of a spill.[28] Howard Teas and his colleagues evaluated mangroves that were transplanted in an oiled area six and 12 months after a spill of medium light crude oil and found that mangroves planted after 12 months grew better than those transplanted after six months.[29]

The seasonal timing of an oil spill may also influence the degree of impact expected. Season of marsh exposure to oil was shown to be an important factor in determining the degree of vegetative impact.[30] Researchers observed little significant mortality of plants exposed during their dormant period, regardless of the freshness of the oil. During the growing season, when plant growth is most active, there is a greater potential for oil-related impacts.[31] Qianxin Lin determined that when south Louisiana crude oil was experimentally introduced to marsh soil in June, photosynthesis, live plant material, and the ability of the plant to regenerate all declined more than when the experiment was performed again in late October.[32]

C. Soil Impacts Versus Plant Impacts

Susceptibility of marshes to soil fouling may vary depending upon soil type, with vegetation impacts being most pronounced in marshes with organic soils.[33] Where organic soils

18. *See* Pezeshki et al., *supra* note 10.
19. Seth Borenstein, *Oil Spill Is the "Bad One" Experts Feared*, Assoc. Press, Apr. 30, 2010, *at* http://www.msnbc.msn.com/id/36878803/.
20. E-mail from Prabhakar Clement, Professor, Auburn University College of Engineering (July 2010).
21. George R. Hampson & E.T. Moul, *No. 2 Fuel Oil Spill in Bourne, Massachusetts: Immediate Assessments of the Effects on Marine Invertebrates and a 3-Year Study of Growth and Recovery of Salt Marsh*, 35 J. Fish. Res. Board Canada 731-34 (1978); Carl Hershner & James Lake, *Effects of Chronic Pollution of a Salt Marsh Grass Community*, 56 Marine Biology 163-73 (1980).
22. Pezeshki et al., *supra* note 10; Ko & Day, *supra* note 12.
23. Steven K. Alexander & James W. Webb Jr., *Seasonal Response of* Spartina alterniflora *to Oil*, *in* Proceedings 1985 Oil Spill Conference 355-57 (1985).
24. S. Reza Pezeshki et al., *Removing Oil and Saving Oiled Marsh Grass Using a Shoreline Cleaner*, *in* International Oil Spill Conference 203-39 (American Petroleum Inst. 1995).
25. *Id.*
26. S.A. Crow Jr., Microbiological Aspects of Oil Intrusion in the Estuarine Environment (1974) (Ph.D. thesis, Louisiana State Univ.); Carl Hershner & Ken Moore, *Effects of the Chesapeake Bay Oil Spill on Salt Marshes of the Lower Bay*, *in* Proceedings: 1977 Oil Spill Conference 529-33 (American Petroleum Inst. 1977).
27. Donald F. Boesch et al., Oil Spills and the Marine Environment 21-23 (Ballinger 1974).
28. E.B. Cowell, *The Effects of Oil Pollution on Salt Marsh Communities in Pembrokeshire and Cornwall*, 6 J. Applied Ecology 133-42 (1969).
29. Howard J. Teas et al., *Mangrove Restoration After the 1986 Refineria Panama Oil Spill*, *in* Proceedings: 1989 Oil Spill Conference 433-37 (American Petroleum Inst. 1989).
30. Jenifer M. Baker, *Seasonal Effects*, *in* The Ecological Effects of Oil Pollution on Littoral Communities 44-51 (E.B. Cowell ed., Applied Science Publishers 1971).
31. D.S. Ranwell & D. Hewett, *Oil Pollution in Poole Harbour and Its Effects on Birds*, 31 Bird Notes 192-97 (1964).
32. Qianxin Lin, Factors Controlling the Impact of South Louisiana Crude Oil on Vegetation and Revegetation of Coastal Wetlands (1996) (Ph.D. thesis, Louisiana State Univ.).
33. *See* Pezeshki et al., *supra* note 10.

occur, microbes that normally break down hydrocarbons may instead utilize natural carbon-based organic matter. In this situation, the time it takes for oil to biodegrade may be slower than normal, particularly where nutrients are not abundant (microbes with abundant carbon sources eventually become nutrient-limited). Soil particle size may be important as well. Soils with more clay particles have been shown to impede O_2 penetration into the soil column and keep soils anaerobic longer (thus potentially extending the amount of time that oil is exposed to plant rhizomes). However, clayey soils may also be less susceptible to oil penetration than sandier soils, which have larger pore spaces capable of being further penetrated than clays. Organic soils have also been shown to be more susceptible to more rapid penetration by oil than mineral soils.[34] Low soil hydrogen ion concentration (pH) can further increase the time that oil persists in soils. DeLaune reported that the highest rate of mineralization of petroleum occurred at pH 8.0 and the lowest at pH 5.0.[35]

D. Organism Response to Oil Exposure

Although the regeneration of plants is essential for marsh recovery, this may or may not translate to the recovery of the important faunal species that use the marsh. The GOM coastal marshes support very productive fisheries and estuarine nursery areas for the early life stages of fish. Salt marshes also provide habitat for important forage species of recreational and commercial fisheries.[36] A major concern is that many marsh species may be negatively impacted by oil toxicity, although many organisms have shown not to be sensitive. In a set of experiments, flatfish (flounder) were placed in close proximity to oil-contaminated soils and were able to detect and avoid high oil concentrations, but not the lower concentrations.[37] Some fish will readily eat foods contaminated at low to medium oil concentrations.[38] Fish densities related to coastal areas have been shown to rebound after spills occur. After the *Exxon Valdez* spill in Alaska, fish densities in intertidal habitats were significantly reduced, but one year later, similar densities were seen in both an impacted site and a reference area.[39] Faunal species' lack of avoidance to low oil concentrations may lead to long-term exposure from contaminated soils long after a spill.[40] M.M. Alexander and colleagues reported bird mortality from a previous oil spill along the St. Lawrence River associated with foraging in oil-contaminated marshes.[41] Research in upper Galveston Bay, Texas, compared oil concentrations from three spills that occurred between 1990 and 1996 and the use of the marsh surface by faunal species. Results suggest remaining weathered oil concentrations found in the sediments did not affect habitat selection by most organisms.[42]

II. Options for Cleaning Oil From Wetlands

When marshes become exposed to oil, the best option for cleanup is not always apparent, and incorrect responses have sometimes induced further impacts. Unlike other spills, such as the *Exxon Valdez*, which occurred along a rocky shoreline, coastal wetlands along the GOM represent a vegetated environment that is less conducive to direct washing. In this region, many cleanup activities may do more harm than good, and often no action may be the best option. A good starting point for deciding on what cleanup technique is most appropriate is to assess how severe the impact is and the likely time frame for recovery.[43] Reported recovery times for wetlands can range from months to decades, depending on conditions (Table 1). As described below, there is a variety of wetland cleanup techniques available to managers after oil exposure has occurred. Site-specific conditions (both the wetland and the degree of fouling) will dictate the most proper technique(s) to use.

A. Low-Pressure Flushing

Low-pressure flushing is a common technique, which uses lower pressure water to move oil away from wetland sites and toward open water where it can be collected. If done correctly, flushing can lift oil from the plants/sediment and push it out of the wetland. This method of cleanup can become damaging if water pressure is too high. High-pressure water can lead to erosion of the sediment, which can create plant loss and lower ground elevations. Worker-traversing in the wetland can also be a problem; careful monitoring and supervision are necessary in this scenario. Irving Mendelssohn and his colleagues found that physical disturbance of soil and vegetation caused by cleanup activities (marsh buggies, etc.) had severe impacts on an oiled marsh in Louisiana.[44] Mobile equipment use and foot traffic should be minimized, and if possible, replaced by the use of boats and boardwalks.

B. Vacuuming/Pumping/Skimming

Pumping and skimming of oil from the water is generally used in conjunction with flushing. This involves physically vacuuming the oil from the water or sediment surface. Pumping and skimming have both proven to be successful at removing large amounts of oil from the affected area. However, this technique will not remove all of the oil, and some

34. *See* Ko & Day, *supra* note 12.
35. Ronald D. DeLaune et al., *Fate of Petroleum Hydrocarbons and Toxic Organics in Louisiana Coastal Environments*, 13 Estuaries 72-80 (1990).
36. *See* Rozas et al., *supra* note 8.
37. Adam Moles et al., *Non-Avoidance of Hydrocarbon Laden Sediments by Juvenile Flatfishes*, 32 Netherlands J. Sea Res. 361-67 (1994).
38. Jorgen S. Christiansen & Steven G. George, *Contamination of Food by Crude Oil Affects Food Selection and Growth Performance, but Not Appetite in an Arctic Fish, the Polar Cod* (Boreogadus saida), 15 Polar Biology, 277-81 (1995).
39. Willard E. Barber et al., *Effect of the* Exxon Valdez *Oil Spill on Intertidal Fish, a Field Study*, 124 Transactions Am. Fisheries Soc'y 461-76 (1995).
40. *See* Moles et al., *supra* note 37.
41. M.M. Alexander et al., *The Impact of Oil on Marsh Communities in the St. Lawrence River*, *in* Proceedings of the 1979 Oil Spill Conference 333-40 (American Petroleum Inst. 1979).
42. *See* Rozas et al., *supra* note 8.
43. Rebecca Z. Hoff, *Fidalgo-Bay: Long-Term Monitoring of an Oiled Salt Marsh*, *in* Proceedings Puget Sound Research 95, 920-26 (Puget Sound Water Quality Authority 1995).
44. Irving A. Mendelssohn et al., *The Effect of a Louisiana Crude Oil Discharge From a Pipeline Break on the Vegetation of a Southeast Louisiana Brackish Marsh*, 7 Oil & Chemical Pollution 1-15 (1990).

Table 1. Documented Cases of Oil Exposure and Marsh Recovery in the Literature

Year	Location	Oil Type	Cleanup Efforts	Recovery Observations	Reference
1977	Virginia Salt Marsh	Louisiana crude oil	n/a	Live plants declined 66% in one year	Bender et al., 1977
1978	Brittany, France	Arabian light, Iranian light, crude oils	Soil removal	Recovery: 5-8+ years	Baca et al., 1987
1992	Delaware River	n/a	Selective vegetative cutting	Estimated full vegetative recovery one year later	Levine et al., 1995
1985	Southern Louisiana	n/a	n/a	*S. alterniflora* had the greatest increase of ground coverage among 3 studied plant species 4 years after spill	Mendelssohn et al., 1993
1974	Chile	Arabian crude, Bunker C	none	Recovery took 20+ years	Baker et al., 1993
1985	Nairn, Louisiana	Louisiana crude	Flushing, vacuuming, trampling	Initial decline in plant cover, most areas recovered in 4-5 years	Fischer et al., 1989; Hester and Mendelssohn 2000; Mendelssohn et al., 1990; Mendelssohn et al., 1993
1969	Wales	Heavy oil	n/a	Initial recovery observed within one year of the spill, vegetation visibly recovered 15 years later even when soil samples revealed remaining oil layer.	Baker et al., 1993
1977	Galveston Bay, Texas	No. 6 fuel	Sorbents, raking	Recovery took 12-19 months	Webb et al., 1981
1984	Galveston Bay, Texas	Light Crude	None, sorbents, flushing	Recovery took eight mos.-2.5 years	Holt et al., 1978

residual oil will remain. The concerns of pumping are similar to that of flushing, in that the physical employment of the apparatus used in the operation may damage the sediment. Russel Kiesling and his colleagues concluded that in some instances, skimmers physically remove plants and sediment along with the oil.[45] The loss of excessive plants and sediment could alter marsh elevations and lead to increased flooding and erosion in adjacent healthy marshes.[46]

C. Vegetation Cutting

Cutting oil-fouled vegetation was used often in the past, but is now reserved for situations where erosion is not a risk or plant species are hardy or undesirable (invasive species). This method has been shown by Scott Zengel and Jacqueline Michel to have severe consequences, such as death of plants, increased erosion, and permanent loss of marshland.[47] Cutting near the base of the plant when oil covers the sediment surface may cause damage to the plant roots and/or eliminate the pathway of O_2 to the roots. A moderate version of cutting involves cutting only the upper parts of the plant after aerial exposure or high tide in order to prevent the oiling of animals; however, Sherwood Gagliano and his colleagues determined that cutting, in general, is not beneficial, especially where wetland loss already occurs due to subsidence and increased flooding, such as the coastal marshes of Louisiana.[48]

D. In-Situ Burning

The burning of marsh and wetland grasses has been practiced for some time as a management strategy, however burning as an oil cleanup technique is a fairly new concept. The National Oceanic and Atmospheric Administration (NOAA) highlighted two cases where in-situ burning was used successfully to remove oil from marshes in Maine and Texas.[49] Burning has been shown to quickly remove large amounts of oil and potentially minimize physical impact. Lin and colleagues discovered that the recovery of a salt marsh after exposure to burning was mainly stipulated by the depth of water over the soil surface.[50] These studies show much promise for burning, but some questions remain as to what specific conditions are

45. Russell W. Kiesling et al., *Evaluation of Alternative Oil Spill Cleanup Techniques in a* Spartina alterniflora *Salt Marsh*, 55 Envtl. Pollution 221-38 (1988).
46. J.H. Vandermeulen et al., *Geomorphological Alteration of a Heavily Oiled Salt Marsh (Ile Grande, France) as a Result of Massive Cleanup*, *in* Proceedings of the 1981 Oil Spill Conference (Prevention, Behavior, Control, Planning) 347-51 (American Petroleum Inst. 1981).
47. Scott Zengel & Jacqueline Michel, Cutting Oiled Marshes: A Review of the Effect on Vegetation Recovery, With Illustrated Examples From Riverine, Salt, and Brackish-Water Environments, HAZMAT Report 95-6, 41 (National Oceanic & Atmospheric Admin. 1995).
48. Sherwood W. Gagliano et al., *Land Loss in the Mississippi River Deltaic Plain*, 31 Transactions Gulf Coast Assoc. Geol. Soc'y 295-300 (1981).
49. NOAA, National Ocean Service, Hazardous Materials Response & Assessment Division, HAZMAT Report 96-1, Responding to Oil Spills in Coastal Marshes: The Fine Line Between Help and Hindrance (1995).
50. Qianxin Lin et al., *Salt Marsh Recovery and Oil Spill Remediation After In-Situ Burning: Effects of Water Burn Duration,* 36 Envtl. Sci. & Tech. 576-81 (2002).

required to have a successful burning. Loren Smith and John Kadlec found that burning should never take place when the potential for flooding is present, because it can adversely affect plant regeneration.[51] Mendelssohn and colleagues also found that marshes may require three years to recover from burning and cause shifts in species dominance over time.[52]

E. Biostimulation/Phytoremediation

Phytoremediation is an interesting technique with positive laboratory data, but there is less information on its use in wetlands.[53] Experimental results show that phytoremediation could be a low-impact cleanup technique for handling residual oil. Phytoremediation, otherwise known as biostimulation, is "the act of adding materials to a contaminated environment to cause acceleration of the natural biodegradation processes".[54] Kenneth Lee and his colleagues explained it as adding nutrients, O_2, and/or oil-degrading microorganisms to the sediment to enhance the natural degradation of oil.[55] Pezeshki and colleagues stated that nutrient additions may be the only conceivable response that could be applied to wetlands already fouled with oil.[56] However, continual additions of nutrients can lead to local eutrophication, and the technique is likely viable only when nutrients are limiting factors.

F. Chemical Responses/Dispersants

Chemical responses can include dispersants, cleaners, and soil oxidizers. Dispersants used today are much less toxic than their first-generation counterparts. However, using dispersants directly in wetlands is not encouraged, since there is less water to dilute them.[57] An alternative to dispersants are cleaners that do not disperse oil, but, rather, allow it to be washed from surfaces, such as rock or vegetation.[58] Cleaners could someday become more common for cleanup in marshes and wetlands, but this method also requires more information on its potential toxicity to organisms.

G. Natural Degradation/No Response

Because of difficult access and sensitivity to physical disturbance, oil exposed to most coastal wetlands along the GOM will probably be left to naturally degrade. This option is often preferred, because oil can readily evaporate and naturally degrade in wetland soils.[59] It also precludes the resulting impact of workers and cleaning equipment associated with other techniques, which may excessively damage soils and push oil further into soils. Natural degradation is often relied on during the final stages of restoration, when most of the readily removed oil has already been cleaned. Leaving marshes to naturally degrade oil may not be sufficient when oiling is heavy or degradation will be slow. Exposed oil left undisturbed may continue to harm marshes, impact wildlife, and remobilize to contaminate other wetland sites.

III. Wetland Recovery: Case Studies and Prospects for the Deepwater Horizon Spill

Because of the current amount of oil in the GOM and the uncertainty of additional spilled oil in the future, there is the potential for a tremendous impact to wetlands along the GOM. The long-term outlook is difficult to predict, because the full extent of the impact has yet to be realized. That said, coastal marshes in the GOM and around the world have proven to be resilient to oil, and numerous recoveries have been reported, although usually after several years (Table 1). It is important to remember that even before the oil spill, coastal marshes within the Mississippi River Delta were already under significant duress, because of land subsidence from inadequate sediment supplies.[60] As problematic as the oil spill may be, inadequate sediment is still the most pressing issue facing coastal wetlands in the GOM.

Although there is uncertainty, there are reasons for some optimism that wetlands in the GOM will recover from this oil spill. Several factors specific to the Deepwater Horizon spill may contribute to a more rapid recovery of coastal marshes and degradation of oil within them. *Spartina alterniflora* and the other common marsh plants along the GOM have proven to be resilient to oil exposure and regenerate, as long as exposure is not too excessive or prolonged. The warmer climate, tidal conditions, and marsh productivity all contribute to an active microbial environment that should promote the natural biodegradation of oil. Also, unlike many past oil spills, oil leaking from the Deepwater Horizon site is about 80 kilometers (50 miles) from the coast. The travel time for oil to reach the coast provides an opportunity for it to be weathered and dispersed, thus reducing its potential impact to wetlands.

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51. Loren M. Smith & John A. Kadlec, *Fire and Herbivory in a Great Salt Lake Marsh*, 66 Ecology 259-65 (1985).
52. Irving A. Mendelssohn et al., Environmental Effects and Effectiveness of In-Situ Burning in Wetlands: Considerations for Oil Spill Cleanup 57, Louisiana Oil Spill Coordinator's Office/Office of the Governor, Louisiana Applied Oil Spill Research and Development Program (1995).
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The amount of damage and time to recovery will likely depend on the nature of the impact. Scenarios that cause the greatest damage to wetlands and require the longest recovery time include marshes that are thickly coated by oil, perhaps deposited by a tropical storm or hurricane, or regularly oil-exposed over multiple years. These scenarios could result in soil-fouling (and the fatality of below-ground plant organs) or the depletion of plant carbohydrate stores—either scenario leads to extensive plant mortality and permanent marsh loss. Where oil exposure is light or periodic, marsh plants are capable of regeneration, and the best option will be to let oil biodegrade naturally. As has been the case so far, managers will need to be watchful and prepare for a variety of management and cleanup techniques, even if it means they end up doing nothing at all.