Oil Spills in Marshes

PLANNING & RESPONSE CONSIDERATIONS

March 2022 Update

DEPARTMENT OF COMMERCE
National Oceanic and
Atmospheric Administration
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FISHERIES AND OCEANS CANADA

AMERICAN PETROLEUM INSTITUTE

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Jacqueline Michel[1], Nicolle Rutherford[2], and Scott Zengel[3]

[1]Research Planning, Inc., Columbia, South Carolina
[2]Office of Response and Restoration, National Ocean Service,
National Oceanic and Atmospheric Administration, Seattle, Washington
[3]Research Planning, Inc., Tallahassee, Florida

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SPECIAL NOTES AND DISCLAIMERS

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American Petroleum Institute

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INTRODUCTION

This report is intended to assist those who work in spill response and planning where fresh and salt marshes are at risk of oil spills. By understanding the basics of the ecology of marshes and learning from past oil spills in marshes, we can better plan for, protect, and make appropriate decisions for how to respond to future oil spills. Along coastal areas, marshes occur in intertidal to supratidal zones, and the marsh fringe is often contaminated by spills on water. In inland areas, marshes occur along the margins of freshwater bodies such as rivers and lakes and can also be exposed to waterborne spills. In many areas of the country, pipelines cross under, through, or adjacent to marshes, making them at risk of interior oiling.

Marshes provide many important ecological services and functions and are habitat to many species. When an oil spill affects these habitats, impacts can be severe; however, impacts from inappropriate response methods can increase these impacts and slow overall recovery.

This report is intended to be a technical “job-aid” for spill response scientists. Our goal was to summarize the scientific literature and experience of past spills in a format that balances between too much detail and too many generalizations. Every spill is a unique combination of conditions–oil type, amount of oil, location of oiling, extent of oiling on the soils and vegetation, vegetation types, time of year, presence of species of concern, degree of exposure to natural removal processes, etc. Responders have to evaluate all of these factors and make a decision on the best course of action, *quickly*. We don’t have the ready answer for how to respond for every spill. However, we hope that we have provided the reader with practical and useful information gleaned from a large number of studies to help them make informed decisions.

We have organized the topics by chapter, with all the references provided at the end of each chapter. Chapter 1, *Marsh Ecology*, provides an overview of marshes and their associated communities. Chapter 2, *Oil Toxicity and Effects on Marshes*, provides information on oil types and summarizes what we know about how oil affects marshes, primarily marsh vegetation. In Chapter 3, *Response*, we discuss what is known on the effectiveness and effects of the different response options appropriate for marshes. Lastly, Chapter 4, *Case Studies*, includes four of the important case studies from which we have learned so much.

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CHAPTER 1. MARSH ECOLOGY

Key Points

- Marshes are wetlands dominated by emergent herbaceous plants that are flooded or have water-saturated soils for at least part of each growing season.
- Marshes are highly productive ecosystems that support complex associations of plants, microbes, and animals.
- Marshes vary widely in types of vegetation, soils, inundation frequency, salt tolerance, and seasonality.

What are Marshes?

The word “marsh” describes a wide range of habitats. In general, marshes are wetlands that are dominated by mainly herbaceous (in contrast to woody), “emergent” vegetation where the vegetation is erect and extends above the water or very wet soils. There are many different types of marshes, ranging from freshwater to saltwater, but all are inundated or saturated with water for various periods of time, often on a regular basis. Marshes can be coastal or inland, connected to a water body or isolated, and are generally fed by surface water, although many are also fed by rain and groundwater. Marsh plants have adaptations that allow them to grow in waterlogged soils; vegetation growing in salt water has adaptations to deal with salt stress.

Marshes support a rich and diverse flora and fauna, serving as important nesting, breeding, spawning, rearing, and feeding habitats for many species of birds, mammals, reptiles, amphibians, fish, shellfish, and other invertebrates. They also provide many ecological and societal services, including primary production, food web support, nutrient recycling, water quality maintenance, sediment and stormwater retention, shoreline stabilization, flooding and storm-surge protection, soil development, fisheries and wildlife production, carbon sequestration, recreational opportunities, and cultural values. Plates 1 and 2 show representative plant and animal species in marshes.

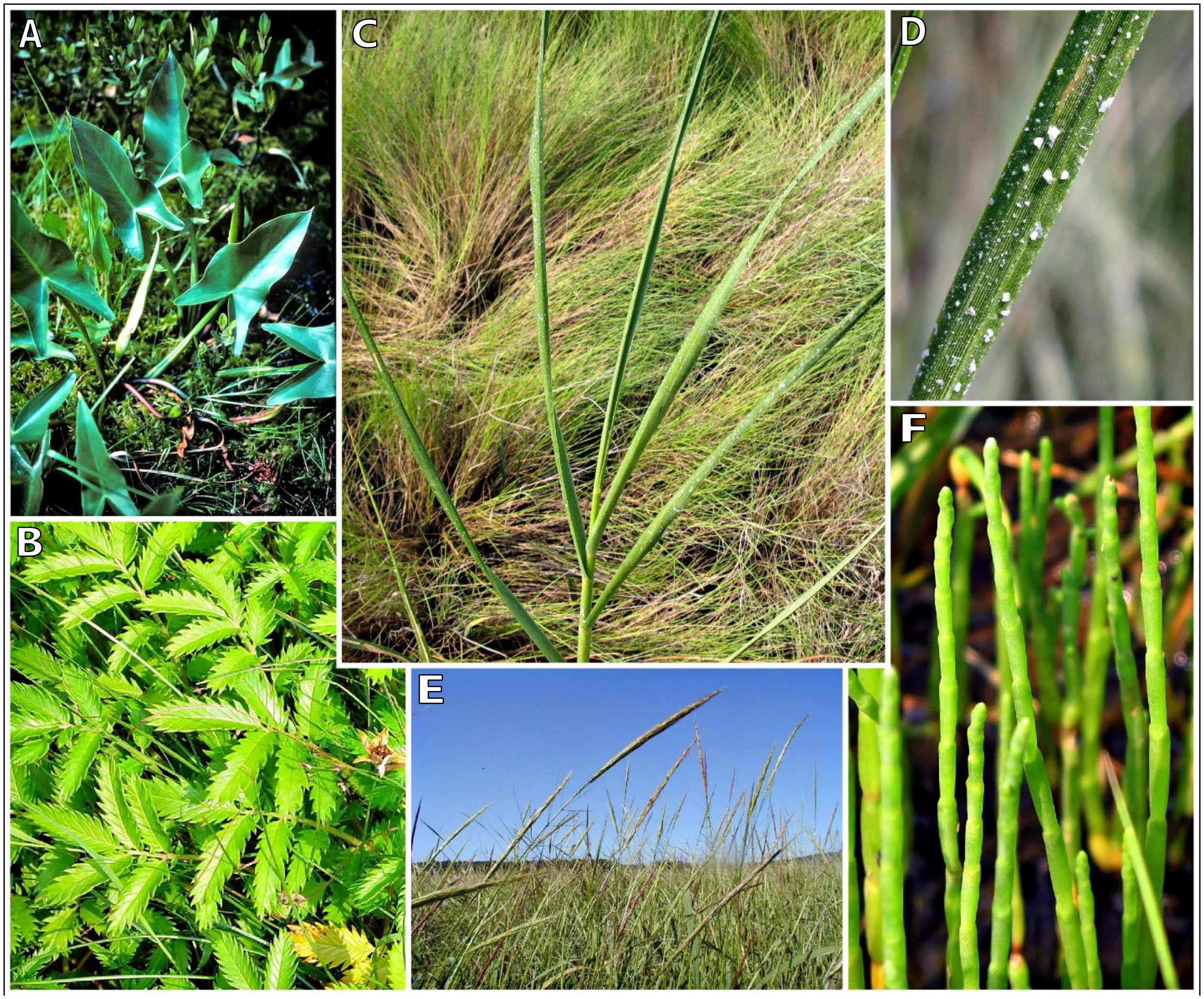

Plate 1: Representative marsh plants. All images reproduced with permission, with rights reserved. A) Green arrow arum (R.A. Howard, Smithsonian Institute). B) Pacific silverweed (Arthur Haines). C) Smooth cordgrass stem with salt meadow cordgrass behind (Sandy Richard). D) Salt crystals on smooth cordgrass stem (Sandy Richard). E) Wild rice (Eli Sagor). F) Virginia glasswort (Sandy Richard).

Plate 2: Representative marsh fauna. All images reproduced with permission, with rights reserved. A) Blue crab (Brian Henderson). B) Light-footed clapper rail (or Light-footed Ridgeway's rail) (Nick Chill). C) Juvenile chinook salmon (NOAA). D) Hine's emerald dragonfly (P. Burton/USFWS). E) Ruddy ducks (Tom Koerner/USFWS). F) Salt marsh harvest mouse (Judy Irving). G) Gulf killifish (Dr. Stephen "Ash" Bullard). H) Whooping crane (Mehgan Murphy).

Types of Marshes

Freshwater Non-Tidal Marshes

Freshwater, non-tidal marshes are common, widespread, and diverse. They are similar in that they are typically dominated by grasses, sedges, and rushes, but otherwise differ in their geologic origins, hydrology, and size (Mitsch and Gosselink 1986). They are often found in poorly drained depressions or basins, near streams, rivers, ponds, and lakes, in oxbows, on floodplains, on deltas, and at the base of steep slopes (Fretwell et al. 1996). Freshwater marshes can be permanently or periodically flooded with inches to feet of water, some have water-saturated soils, and some may dry out completely on a seasonal or periodic basis. Water levels are controlled both directly and indirectly by precipitation, with many marshes intercepting flood waters from lakes and rivers, surface runoff, or groundwater (Fretwell et al. 1996).

Freshwater, non-tidal marshes are found throughout the United States and Canada and include prairie potholes, wet meadows, wet prairies, playas, and vernal pools. Prairie potholes are numerous, shallow depressions associated with the formerly glaciated landscape of central North America, particularly Iowa, Wisconsin, Minnesota, and North and South Dakota (van Der Valk and Pederson 2003). Wet meadows and wet prairies are grasslands with very wet soils but without standing water most of the year that are common to the Midwest and southeastern United States. Playas are circular, shallow depressions that are typically found in the southern great plains, particularly in northern Texas and eastern New Mexico (Mitsch and Gosselink 1986; Tiner et al. 2002). Vernal pools are small, seasonally flooded wetlands that dry up completely in the summer and are found throughout the United States, but occur in the highest numbers on the Pacific coast (Zedler 2003). The Florida Everglades contain the largest single freshwater marsh system in the United States (Mitsch and Gosselink 1986). Although each of these systems has unique features, they share characteristics such as hydric soils, vegetation adapted to wet conditions, and wetlands-dependent wildlife.

Soils in freshwater non-tidal marshes are typically alkaline, highly organic, mineral soils of sand, silt, and clay with high concentrations of calcium. In some cases, these marshes can have organic or peat soils. Nutrient levels in the soils are high, resulting in highly active bacterial communities that rapidly decompose vegetative litter and fix nitrogen (Mitsch and Gosselink 1986). They vary in exposure to physical processes such as water currents and waves.

Although geographically and geologically diverse, freshwater non-tidal marshes are dominated by similar types of grasses, sedges, rushes, and other water-adapted plants. Dominant grasses may include common reed or roseau cane (in Louisiana) (*Phragmites australis*), prairie cordgrass (*Spartina pectinata*), annual wild rice (*Zizania aquatica*), and maidencane (*Panicum hemitomon*), for instance. Typical sedges may include *Carex* spp., *Cladium* spp. (sawgrass), and bulrushes (e.g., *Scirpus* and *Schoenoplectus* spp.). Other common plants can include various rushes (*Juncus* spp.), cattails (*Typha* spp.), arrowhead (*Sagittaria* spp.), pickerelweed (*Pontederia cordata*), and horsetail (*Equisetum* spp.) (Mitsch and Gosselink 1986)[1].

Tidally Influenced Marshes

Tidally influenced marshes represent a salinity continuum from freshwater to fully marine waters with several different salinity regimes in between. For the purposes of this document, tidally influenced marshes will be divided into tidal freshwater marshes and saltwater marshes, the latter including brackish and intermediate marshes.

Tidal Freshwater Marshes

Tidal freshwater marshes occur close enough to the coast to undergo daily changes in water levels driven by tides, but with salinity ranging from zero to less than 0.5 parts per thousand (ppt). They occur in the uppermost portion of the estuarine zone. Tidal freshwater marshes can experience significant tidal ranges, sometimes of a greater amplitude than those tides experienced at the mouth of the river due to constriction of the water as it moves inland (Mitsch and Gosselink 1986; Odum 1988; Tarnocai and Zoltai 1988).

Tidal freshwater marshes can be found on the Atlantic, Pacific, Gulf, and Arctic coasts of North America, and are usually associated with large river systems (Leck et al. 2009; Mitsch and Gosselink 1986; Odum 1988). In the U.S. they are most extensive on the middle and southeast Atlantic coasts, northern Gulf of Mexico coast, and in Alaska. On the Pacific coast, generally steep topography and mountains limit the size and drainage of the estuaries, leaving few areas with broad drowned river basins that permit the development of extensive freshwater systems. Consequently, the only extensive tidal freshwater marshes along the U.S. west coast are found in the San Francisco Bay Delta, Columbia River, and Puget Sound (Leck et al. 2009).

Sediments in tidal freshwater marshes typically contain clay, silt, and fine organic matter with minor amounts of sand that have been deposited from upriver and terrestrial sources (Odum et al. 1984). The amount of organic material varies greatly, with Atlantic and Gulf coast sediments containing between 10

[1]All plant names are from the USDA PLANTS database (2022). Animal names are primarily from the Integrated Taxonomic Information System (2022).

to 40% organic matter, and Pacific coast sediments ranging from 5% to around 60% (Thom et al. 2002; Josselyn 1983).

Tidal freshwater marshes are characterized by salt-intolerant or mildly tolerant plant species, typically a diverse community of emergent grasses, sedges, rushes, and other herbaceous plants. Typical plants in Atlantic coast tidal freshwater marshes can include wild rice, cattails, and green arrow arum (*Peltandra virginica*), as well as pickerelweed and broadleaf arrowhead (*Sagittaria latifolia*). Gulf coast tidal freshwater marshes, such as in Louisiana, can include many of the same species, as well as bulltongue arrowhead (*Sagittaria lancifolia*), maidencane, spikerush (*Eleocharis* spp.), giant cutgrass (*Zizaniopsis miliacea*), and common reed. On the Pacific coast, typical plant species include mountain rush (*Juncus arcticus*), Pacific silverweed (*Argentina egedii*), hardstem bulrush (*Schoenoplectus acutus*), and cattails. Tidal freshwater marsh plant communities are highly influenced by flooding duration, changes in salinity and/or precipitation, and changes in elevation as well as other factors, and vary seasonally, between years, and over longer time frames (Leck et al. 2009). The marsh fringe can be exposed to riverine and tidal currents and some wave action, whereas the inner marsh is very sheltered.

Because tidal freshwater marshes contain such a wide diversity of habitats and plant communities, they support many species of birds, mammals, reptiles, amphibians, fish, and invertebrates. Many birds use tidal freshwater marshes for breeding, nesting, rearing, and feeding. Likewise, numerous species of fish use these marshes as breeding, spawning, and nursery grounds, ranging from year round residents like sunfishes, minnows, and catfish, to anadromous fish such as salmon, herring, and shad (Mitsch and Gosselink 1986).

Tidal Saltwater Marshes

There are several types of tidal saltwater marshes, including salt, brackish, and intermediate marshes. They are defined by their average salinity. Salt marshes are regularly flooded by the highest salinities, while brackish and intermediate marshes are progressively less salty. Varying salinity and tidal regimes influence the composition of the plant community found within each marsh type. For the purposes of this document, these specific types of saltwater marshes will be referred to collectively as salt marshes.

Salt marshes are tidally influenced and experience salinities ranging from 0.5 ppt up to seawater (≥30 ppt). The salinity gradient is nearly continuous from the ocean to the head of the saltwater intrusion into the estuary, until the saltwater signature is drowned by the inflow of freshwater. Tidal ranges in salt marshes are from less than 0.5 meters (m) on the Gulf Coast, to typically 2-3 m on the East Coast, and in some areas of the Pacific coast, greater than 3 m (Pennings and Bertness 2001; Seliskar and Gallagher

1983). Arctic coast salt marshes generally have <2 m tidal ranges, though some locations have 2-3 m tides and even >5 m tides in certain embayments. Salt marshes have many adaptations to tolerate salt stress, as listed in Table 1-1.

Table 1-1. Adaptations of salt marsh plants to salt stress (modified from Tiner 1999).

Adaptation Type	Examples
Morphological	Salt secretion glands (to eliminate excess salt; see Plate 1D) Succulent stems and leaves (increased water retention to maintain internal salt balance Waxy leaf coatings (to minimize contact with sea water) Salt concentration in specialized hairs Reduced leaves (to minimize exposure to salt and evapotranspiration)
Physiological	Salt exclusion (reduced salt update by roots) High ion update (lowers osmotic potential of cell sap) Dilution of salts Accumulation of salt in cell vacuoles
Other	Salt stress avoidance (by occupying higher levels of salt marsh) Periodic shedding of salt-saturated organs

Salt marshes are found on all tidally influenced coasts of the United States, but the vast majority of the nation’s salt marshes (97%) are located on the Atlantic and Gulf coasts. 58% of the nation’s total salt marsh area is located on the Gulf Coast, while the middle and south Atlantic coast contains 37% of the nation’s salt marsh area. Of the Gulf Coast states, Louisiana contains the most salt marsh habitat, with 42% of the nation’s total, while South Carolina has the largest total area of salt marsh (>9%) of the Atlantic states. In total, the south Atlantic and Gulf coasts contain nearly 80% of the nation’s salt marshes (Field 1991).

In contrast, much of the Pacific coast outside of Alaska and Canada has few large saltwater tidal habitats, contributing only 3% of the salt marshes in the U.S. Of the 3%, 75% of those salt marshes are located in California (Field 1991). As described earlier for tidal freshwater marshes, on the west coast, mountains limit the location and size of the estuaries, with estuaries and lagoons constituting less than 20% of the shoreline (Macdonald 1977). Although small in area, California salt marshes are important habitats for several threatened and endangered species.

Salt marsh sediments vary widely in their composition and are determined by the sediment source and tidal current patterns. Sediments may be river silt, organic material, or sand and clay originating from marine sources. Large variations in sediment organic content across regions and within individual marshes can occur as a result of different rates of production and below-ground decomposition (Odum 1988; Zedler and Callaway 2001). The organic content of the sediment, in addition to the elevation and drainage, are more important than the source of mineral sediment in determining marsh productivity (Mitsch and Gosselink 1986).

Salt marshes are characterized by salt-tolerant flowering plants, including salt-tolerant grasses, rushes, and sedges. In salt marshes of the entire east coast and much of the Gulf coast, smooth cordgrass (*Spartina alterniflora*) is the most dominant species. In some Gulf coast marshes, needlegrass rush or black needlerush (*Juncus roemerianus*) is dominant. Other species common in east and Gulf coast salt marshes include salt meadow cordgrass (*Spartina patens*), saltgrass (*Distichlis spicata*), Virginia glasswort (*Salicornia depressa*), and turtleweed (*Batis maritima*) (Mitsch and Gosselink 1986; Odum 1988; Wiegert and Freeman 1990; Zedler and Callaway 2001). In brackish and intermediate marshes, mixtures of the above species and a subset of species also found in tidal freshwater marshes can occur. On the Gulf Coast, in Louisiana for example, *Spartina patens* is often dominant in brackish and intermediate marshes, along with *Distichlis spicata*, *Schoenoplectus* spp., *Sagittaria lancifolia*, and a variety of other species, depending on salinity.

On the Pacific coast, *Spartina alterniflora* is a non-native, invasive species. In the California marshes, California cordgrass (*Spartina foliosa*), pickleweed (*Salicornia* spp.), saltgrass, and turtleweed are common species (Macdonald 1977; Zedler 1982). The plant communities of Oregon, Washington, and Alaska share some species in common with the California marshes, including glasswort and saltgrass, but have no California cordgrass or turtleweed (Zedler 1982). Alkaligrass (*Puccinellia* spp.) and extensive stands of sedges (*Carex* spp., *Schoenoplectus* spp.) and rushes are common (Macdonald 1977; Seliskar and Gallagher 1983).

Arctic coast salt marshes are dominated by species such as Hoppner's sedge (*Carex subspathacea*), Ramensk's sedge (*Carex ramenskii*), creeping alkaligrass (*Puccinellia phryganodes*), several other *Carex* and *Puccinellia* species, Danish scurveygrass (*Cochlearia groenlandica*), Fisher's tundragrass (*Dupontia fisheri*), and saltmarsh starwort (*Stellaria humifusa*) (NatureServe Explorer 2022).

Salt marsh species and forms differ depending on the frequency and duration of flooding, as shown in Figure 1-1. The lower, regularly flooded zone ("low marsh") is usually dominated by one species, such as smooth cordgrass along the Atlantic and Gulf coasts. On the Pacific Northwest coast including Canada, the low marsh may be dominated by nearly monotypic stands of Lyngbye's sedge (*Carex lyngbyei*), the northwest analogue to the cordgrass marshes of the Atlantic and Gulf coasts. Or, as depicted in Figure 1-1, it may host a mixed community of plants that includes saltgrass, marsh jaumea (*Jaumea carnosa*), and pickleweed, among others (Seliskar and Gallagher 1983). The higher, irregularly flooded zone ("high marsh") has more diverse vegetation because the plants have less inundation stress and fewer fluctuations in salinity and temperature than the plants in the low marsh. The salt marsh fringe is exposed to tidal currents and wave action, whereas the inner marsh is sheltered from these processes. In addition, in northern marshes on the Atlantic, Pacific, and Arctic coasts, ice, including ice rafting and scour and associated sediment dynamics, as well as permafrost and permafrost melt (in the Arctic), can be major physical factors that influence salt marsh plant distribution.

Salt marshes are some of the most productive ecosystems in the world, typically exceeding the production of the most successful agricultural activities. These highly productive habitats support abundant invertebrates, fish, and wildlife, and produce large quantities of organic material that play important roles in marsh and estuarine food webs. They are important feeding, breeding, nesting, and rearing habitat for numerous fish, mammals, invertebrates (e.g., crabs, shrimp, insects), and birds, including migratory waterfowl. Salt marshes are particularly valuable habitat as nurseries for commercial and recreationally important fish and shellfish species, as well as for native and at-risk species (Gewant and Bollens 2012).

General Life History Information

Annuals vs. Perennials

Annuals are plants that complete their entire life cycle typically within a year. They germinate, flower, produce seeds, and die and a new population begins anew from seeds each year. All their roots, stems, and leaves die annually.

Perennials live for two or more years, overwintering and producing new growth, flowers, and seeds from the same rootstock. In some perennials, the leaves, stems, and flowers die back in the fall or winter, and the plant regrows in the spring from the rootstock. In other perennials, the plant retains its aboveground structures year-round. Perennials can reproduce by seeds, but have evolved a variety of vegetative cloning strategies, including the production of bulbs, tubers, and rhizomes (thick parts of plants that grow horizontally under or on the ground and send out roots and shoots). Vegetative cloning strategies such as rhizome growth allow the development of dense, single-species stands of vegetation as seen in the smooth cordgrass-dominated salt marshes of the Atlantic and Gulf coasts.

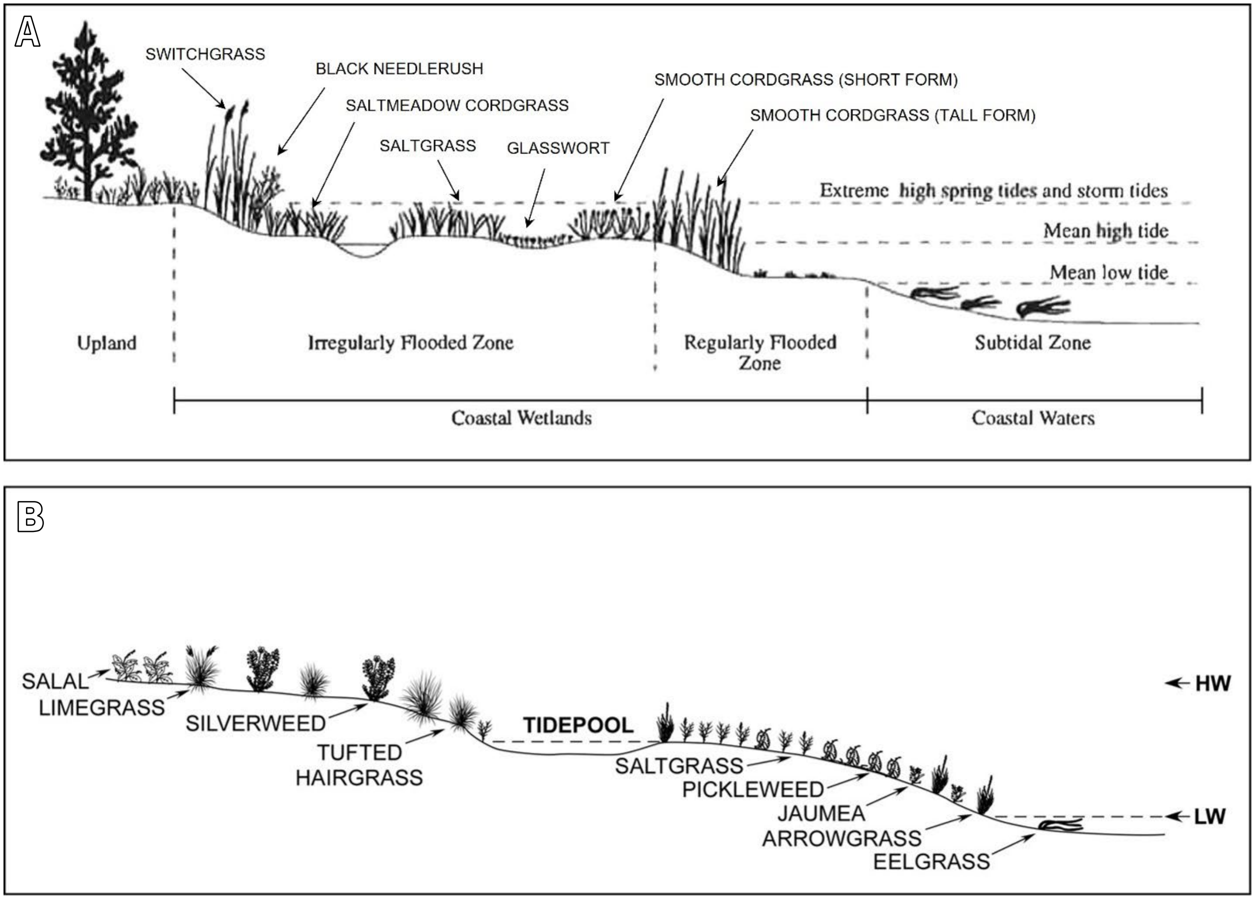

Figure 1-1. Tidal salt marsh zonation. A) Mid-Atlantic salt marshes based on frequency of tidal flooding. The low marsh is flooded at least once daily; the high marsh is flooded less often (after Tiner and Burke 1995). B) Typical zonation of marsh plants in a Pacific Northwest tidal salt marsh. The lateral extent of the zones depends on the slope and may range from a few meters to hundreds of meters (from Seliskar and Gallagher 1983).

Seasonality

As discussed earlier, annual plants complete their entire life cycle in one year or less. Some summer annuals sprout, flower, seed, and die in less than one month. Other annual plants may take several months to complete their life cycle. Their seeds persist until the environmental conditions are right for germination, thus starting a new generation. Annual plants come in two forms: summer and winter. Summer annuals germinate and die in a single season (spring, summer, or fall). Winter annuals germinate in the fall or winter, bloom in the winter or early spring, and then die once they set seeds. The seeds of annuals are the sole source of the next year's growth.

Perennial plants, on the other hand, live through multiple seasons and years. In warm climates, perennials may grow year-round, while in climates with pronounced seasonality, growth is limited to the growing season. In these instances, the perennials enter a period of dormancy with associated senescence (die back) of the aboveground vegetation. Other perennials may not be truly dormant, but just stop or slow growth if the temperatures are too low or there isn't enough light. In these instances, once the environmental conditions are correct, the plant resumes growth. Most vegetative growth of plants in the tidal marshes of the east and Gulf coasts occurs from March to November (Eleuterius 1990). However, *S. alterniflora*, the dominant plant in these marshes, can grow year-round, but more slowly in the winter months (Gosselink 1984).

Most of the plants found in freshwater non-tidal and tidal habitats are a mix of annuals and perennials. These marshes exhibit pronounced seasonality with changes in plant community dominance as the seasons progress. As the annuals flower and die, their seeds are dispersed to lie dormant until the environmental conditions are right for germination, thus starting a new generation. Salt marshes, on the other hand, are dominated by perennial plants, which have adapted to handle the more extreme environment created by high or fluctuating salinities and varying flooding regimes.

Fauna

Marshes support a rich and diverse assortment of animals. The high productivity, diverse habitat structure, and flood regimes of these transitional areas between terrestrial and aquatic habitats attract and support numerous invertebrates, fish, amphibians, reptiles, mammals, and birds. Marshes are critically important habitats for migratory and resident bird species including numerous ducks, wading birds, and shorebirds, and are used by nearly one-third of North American birds for shelter, resting, feeding, nesting, breeding, and rearing habitat (Fretwell et al. 1996 in Stewart, 1996). Nearly two-thirds of the continental United States' waterfowl reproduce in the prairie pothole marshes of the Midwest. In addition, tidally influenced marshes function as the nursery grounds for numerous recreational and commercial fisheries including shrimp, crabs, and wide variety of fish species. Freshwater marshes also provide refuge, spawning, and rearing habitat to a variety of amphibians and reptiles including the American alligator, and numerous species of turtle, snakes, and frogs. Common mammals that either live in marshes or visit frequently include muskrats, otters, minks, and raccoons.

Marshes are home to numerous threatened and endangered species. In fact, some estimates are that greater than 40% of the nations endangered and threatened species rely directly or indirectly on wetlands for survival (Department of Environmental Conservation, Vermont 2011; Environmental Law Institute 2011). Although the term wetlands encompasses more than just marshes, this statistic illustrates the importance of these habitat types. Examples of threatened and endangered species that rely on marsh habitats include the Everglades snail kite, Lower Keys marsh rabbit, wood stork, chinook salmon, salt marsh harvest mouse, light-footed clapper rail (or light-footed Ridgeway's rail), Hine's emerald dragonfly, and the whooping crane.

For Further Reading

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CHAPTER 2. OIL TOXICITY AND EFFECTS ON MARSHES

Key Points

- Oil type is one of the major factors determining the degree and type of impacts on marshes.
- Lighter oils are more acutely toxic than heavier oils; however, when spilled offshore, light oils seldom cause extensive damage because they spread into thin slicks.
- Heavy refined oils and most crude oils affect marshes through physical smothering of both leaves and soils. The oil weathering and emulsification prior to landfall reduces the initial toxicity of the oil; although emulsification can worsen the degree of smothering and oiling persistence on the marsh.
- The extent of oiling on the vegetation is a key factor. If only parts of the leaves are oiled, marshes can often recover quickly, within one growing season.
- Exposure to waves and currents that speed oil removal is another key factor. Other factors include degree of contamination of the soils, the types of soils, time of year, and different sensitivities among plant species.

Oil Groups

Oils can be divided into five groups as shown in Table 2-1 based on their general behavior, persistence, and properties. Each group is defined by a range in specific gravity, defined as the ratio of the mass of the oil to the mass of freshwater, for the same volume and at the same temperature. If the specific gravity of the oil is less than the specific gravity for the receiving water (freshwater = 1.00 at 4°C; seawater = 1.03 at 4°C), it will float on the water surface. API gravity[2] is another property that is often reported and can be used to characterize an oil's behavior.

Factors Affecting the Impacts of Oil on Marsh Vegetation

Oil Type

The type of oil spilled influences the potential type and degree of impacts to marshes because of differences in behavior, persistence, and toxicity. In this section, case histories and summaries are provided to indicate the likely impacts from spills of: 1) light refined products (mostly Group 2 oils because Group 1 oils usually evaporate quickly); 2) light to medium crude oils (mostly Group 3 oils); and 3) heavy crude oils and heavy refined products (Group 4 oils).

[2] API = (141.5/specific gravity) - 131.5. An API of 10 is equal to a specific gravity of 1.00; an API of 45 is equal to a specific gravity of 0.80. Note that API gravity has an inverse relationship with specific gravity.

Table 2-1. Oil groups and their characteristics.

Group 1: Gasoline Products
- Specific gravity is less than 0.80; API gravity >45
- Very volatile and highly flammable
- Evaporate and dissolve rapidly (in a matter of hours)
- Narrow cut fraction with no residues
- Low viscosity; spread rapidly into thin sheens
- Will penetrate substrates but are not sticky
- High acute toxicity to animals and plants

Group 2: Diesel-like Products and Light Crude Oils
- Specific gravity is 0.80-0.85; API gravity 35-45
- Moderately volatile and soluble
- Refined products can evaporate with no residue
- Crude oils can have residue after evaporation is complete
- Low to moderate viscosity; spreads rapidly into thin slicks; not likely to form stable emulsions
- Are more bioavailable than lighter oils (in part because they persist longer), so are more likely to affect animals in water and sediments

Group 3: Medium Crude Oils and Intermediate Products
- Specific gravity of 0.85-0.95; API gravity 17.5-35
- Moderately volatile
- For crude oils, up to one-third will evaporate in the first 24 hours
- Moderate to high viscosity; will spread into thick slicks
- Are more bioavailable than lighter oils (because they persist longer), so are more likely to affect animals and plants in water and sediments
- Can form stable emulsions and cause long-term effects via smothering or coating

Group 4: Heavy Crude Oils and Residual Products
- Specific gravity of 0.95-1.00; API gravity of 10-17.5
- Very little product loss by evaporation or dissolution
- Very viscous to semi-solid; may be heated during transport
- Can form stable emulsions and become even more viscous
- Tend to break into tarballs quickly
- Low acute toxicity to biota
- Penetration into substrates will be limited at first, but can increase over time
- Can cause long-term effects via smothering or coating, or as residues on or in sediments

Group 5: Sinking Oils
- Specific gravity of >1.00; API gravity <10
- Very little product loss by evaporation or dissolution
- Very viscous to semi-solid; may be heated during transport or blended with a diluent that can evaporate once spilled
- Low acute toxicity to biota (though may have some toxicity if blended with a lighter, more - toxic diluent)
- Penetration into substrates will be limited at first, but can increase over time
- Can cause long-term effects via smothering or coating, and as residues on or in sediments

Due to several newer or unconventional oils that may be encountered by responders, some additional oil types are listed below in relation to oil groups and types. Light shale oil crudes, such as Bakken and Eagle Ford crudes, are usually considered Group 2 oils (very light crudes). Low sulfur fuel oils (LSFO) can range from Group 3 to Group 4 oils (intermediate to heavy residual products), depending on type and source. Diluted bitumen (dilbit) has characteristics of Group 3 oils (medium crude oils) when initially spilled but can weather rapidly to be more like Group 4 oils (heavy crude oils). Examples and case histories of spills of newer or unconventional oils into marshes are limited, but understanding how they fit into oil groups and types provides a starting point for consideration of how they may behave in marshes.

Light Refined Oil Products

Light refined products, such as jet fuel, kerosene, No. 2 fuel oil, home heating oil, and diesel, have been shown to have the highest acute toxic effects on marsh vegetation. Appendix A is a summary of the results of spill studies and field/greenhouse experiments of light refined products on marshes. These types of oil have low viscosity and high rates of loss by evaporation and dispersion into the water column under even low-to-moderate wave energy. When spilled on open water, they usually spread into thin slicks and sheens and often do not persist long enough to cause significant shoreline oiling. As noted in the case studies discussed below, those spills that did result in extensive plant mortality and long-term impacts involved large volumes released to sheltered waterbodies, resulting in heavy oiling of marsh habitats.

> In all the tables in the Appendices, the last column shows what the study results reported as years to "recovery," which usually meant vegetative growth (mostly aboveground biomass, stem density, or plant cover) that is comparable to unoiled vegetation. It should be noted that this definition of recovery is incomplete because it is based on just one metric of marsh services and functions. Very few studies considered other metrics, particularly belowground biomass or animals living in the marsh.

The 185,000 gallons of No. 2 fuel oil from the T/B *Florida* in 1969 in Buzzards Bay, Massachusetts is one of the most famous spills in the literature, partially because many plants and animals were killed, but also because it was close to the Woods Hole Oceanographic Institution where many then- or now-famous scientists became involved in studies of the spill for nearly 40 years. Thus, it is discussed in detail as one of the case studies included in Chapter 4.

In 1974, there was another spill in Buzzards Bay of 3.17 million gallons of No. 2 fuel oil from the T/B *Bouchard 65* that affected a different marsh and has also been well studied. Three years later, Hampson and Moul (1978) documented complete mortality in heavily oiled marshes and significant erosion of the marsh edge. Invertebrate infauna abundance in marsh soils was reduced by 92%. By 1991, Hampson (2000) reported that the remaining salt marsh vegetation had slowly recovered, but the peat substrate had been permanently eroded, leaving only a sand and gravel beach.

Burger (1994) and chapters therein summarized the impacts of a release of 567,000 gallons of No. 2 fuel oil from a pipeline at the Exxon Bayway refinery into the Arthur Kill on 1-2 January 1990. By the first summer, they documented that 7.6 hectares (ha) of mostly *S. alterniflora* had been killed (15% of the affected area), and 2.8 ha were oiled but recovering. There was also high mortality (>67%) of ribbed mussels (*Geukensia demissa*) close to the spill source, and fiddler crab (*Uca* spp.) mortality and sublethal effects were noted. In 1993, after three growing seasons, there was no recovery of most of the dead vegetation (Burger 1994). Vegetation recovery was observed after restoration planting of *S. alterniflora* in 1993-1996 into areas denuded by the spill, even though residual soil oiling was still relatively high (Bergen et al. 2000).

Many field and greenhouse experiments where marsh plants were exposed to No. 2 fuel oil (see Appendix A for details) have found that:

- No. 2 fuel oil can be highly toxic to salt marsh vegetation and more toxic than other types of oil under similar exposure conditions.
- The severity of impacts was directly related to the amount of plant covered by the oil. Studies by Booker (1987) supported the hypothesis that oil exposure affected cell membrane permeability, which would reduce tissue viability through an impaired ability to maintain chemical balances and metabolism in the cells.
- There was a dose-response relationship between the degree of oil in the marsh soils and impacts to plants.
- Both direct physical damage to contacted tissues plus translocation of toxic components of the oil from stems to the root system caused death or a reduction in the ability of the root system to regenerate shoots.

However, not all spills of light refined products result in high mortality of vegetation. NOAA responds to many spills of diesel from fishing vessels, where most of the oil quickly spreads into thin slicks and is dispersed or evaporated, such that shoreline oiling is light and rapidly removed by natural processes. The April 2004 Kinder Morgan pipeline spill in a diked marsh in San Francisco Bay, California did not penetrate into the clayey soils along the channel banks, so there was mortality of fish and invertebrates but little plant mortality.

Interpreting the Oil Loading in Field and Greenhouse Experiments
Most experiments report the oil loading in terms of the number of liters per square meter (L/m^2) of oil applied to the surface of the treatment area (field plot or potted plant). Converting this dose to an oil thickness is complicated because of the variable surface area of the vegetation. However, ignoring the surface area of the vegetation, the thicknesses of different doses are:

1 L/m^2 = 0.1 cm	4 L/m^2 = 0.4 cm	8 L/m^2 = 0.8 cm	24 L/m^2 = 2.4 cm (1 inch)

Shoreline Cleanup Assessment Technique (SCAT) thickness terms:

Cover = <0.1 cm	Coat = >0.1 cm to <1 cm	Thick = >1 cm

In summary:

- Light refined products such as No. 2 fuel oil, diesel, kerosene, and jet fuels do have high acute toxicity to marsh plants and associated communities, and there is a strong dose-response relationship.
- Spill events where large amounts of these kinds of oils get transported into and contained within marshes will likely result in plant and fauna mortality.
- Where the rhizomes die (rather than just the aboveground vegetation dying back), recovery depends on regrowth from plants outside the oiled area; thus, spills affecting large areas may not recover quickly.
- Spills in confined waterways, where the oil is not able to spread out and strands on the shoreline quickly, have the highest risk of impact.
- Offshore spills, small spills, and those where the oil is dispersed by wave action before stranding onshore have a lower risk of impacting sensitive marsh habitats and associated plant and animal communities.

Light to Medium Crude Oils

Light to medium crude oils (including light shale oil crudes) can range widely in terms of their fate and effects on marshes, depending on their chemical composition and the degree of weathering prior to stranding on the marsh. Appendix B lists representative spills and experiments to demonstrate the range of impacts under different conditions. There have been several summaries of the literature on the impacts of crude oil on the marshes of U.S. Gulf Coast (Pezeshki et al. 2000; DeLaune et al. 2003; Mendelssohn et al. 2012; Michel and Rutherford 2014; Pezeshki and DeLaune 2015; Zengel et al. 2022a).

Cowell (1969) was the first to note the differences due to weathering of oil at sea on the effects of two large spills of light Kuwait crude in 1967 on U.K. marshes: the spill from the *Chryssi P. Goulandris* that stranded within hours after the release caused much higher mortality of plants and animals than the spill from the *Torrey Canyon* that stranded after eight days of weathering at sea. This effect was also evident at the *Deepwater Horizon* oil spill where oil was released at the seafloor, rose through approximately 1,500 m of water, was treated by dispersants both subsea and on the surface, and had to be transported by wind and currents for 80-300 kilometers (km) through warm Gulf of Mexico waters to reach the shoreline. Many of those marshes with a heavy thick layer of oil on the marsh vegetation and soils died; those with moderate and light oiling were less impacted and the vegetation recovered or was recovering more quickly (Lin and Mendelssohn 2012; Hester et al. 2016; Zengel et al. 2022a; see case history in Chapter 4).

Crude oil releases from pipelines directly into marshes undergo limited weathering processes and thus tend to result in higher mortality and longer recovery times. A spill of 12,600 gallons of Louisiana crude into a brackish marsh in Louisiana in April 1985 caused nearly complete mortality of about 20 ha, and recovery of the vegetation took four years (Mendelssohn et al. 1993; Hester and Mendelssohn 2000). This amount of oil, if evenly spread throughout the 20 ha, would be at a loading of 0.28 liters/square meter (L/m^2), which is much lower than what is normally found to be toxic to plants based on greenhouse experiments (compare with greenhouse studies in Appendix B). Yet, there was extensive mortality, likely because of a lack of chemical weathering before the oil came in contact with the marsh and minimal physical removal processes, resulting in prolonged exposure.

When reviewing the results of the greenhouse and field experiments, it is very important to understand if the oil was weathered prior to oiling and how the oil was applied–because it varies widely. This information is briefly summarized in the various tables in the appendices, but a full understanding can only be gained from review of the methods of each study. These studies also varied in terms of the water level above the plants during oil exposure, the amount of oil applied to the vegetation and/or soils, and month of exposure, all of which influence how plants respond to oiling.

In summary:

- Crude oils can have acute, short-term toxicity if relatively fresh oil comes in contact with the plants and if most of the plant surface is covered by the oil, but recovery can often occur quickly. These effects are reduced when oil weathers prior to stranding.
- Crude oils can also cause physical smothering, as discussed in the next section on heavy oils.
- It is difficult to summarize the impacts of crude oil spills on marshes because of the range of oil characteristics and spill conditions and the importance of other factors.
- Most of the factors controlling the initial impacts and recovery rates from exposure to crude oils are discussed later in this chapter.

Heavy Crude Oils and Refined Oil Products

Heavy crude oils (including crude oils derived from tar sands) and heavy refined oil products, such as heavy fuel oil, Bunker C, No. 6 fuel oil, and intermediate fuel oils (IFO) 180 and 380, are thought to affect marsh vegetation primarily via physical effects from coating and smothering of the vegetation and/or soil surface because they generally have low amounts of acutely toxic compounds. Studies of these kinds of spills were identified (summarized in Appendix C), and some of the key points are discussed below.

The February 1970 spill of nearly 3 million gallons of Bunker C oil from the T/V *Arrow* in Chedabucto Bay, Nova Scotia, heavily oiled a sheltered lagoon containing *S. alterniflora* marshes and mud flats. No cleanup was conducted, thus there was chronic re-oiling over time. There was high mortality of the vegetation and common periwinkles (*Littorina littorea*), which took over six years to recover (Thomas 1978). Soft-shell clams (*Mya arenaria*) in the adjacent tidal flat showed initial high mortality. This spill showed that chronic re-oiling and persistence of heavy oil accumulations can have long-term impacts to marsh vegetation and fauna.

The 1974 T/V *Golden Robin* spill of Bunker C fuel oil in New Brunswick showed that aggressive manual and mechanical treatment (see Appendix C), even of heavily oiled marshes, can result in slower recovery compared to natural recovery or light treatment (Vandermeulen and Jotcham 1986). Aggressive treatment increased the amount and persistence of oil in the soils because oil was driven into the soils where it could not weather as readily as it would have at the surface. This lesson was learned again during the Bunker C spill from the M/V *Westwood Anette* in British Columbia, where Challenger et al. (2008) documented extensive vegetation damage and increased soil contamination in areas where aggressive oil and soil removal and trampling occurred (at the insistence of local stakeholders), compared to untreated or carefully treated areas.

The barge *STC-101* spill of No. 6 fuel oil in Chesapeake Bay (Hershener and Moore 1977) was one of several studies that showed an increase in net productivity of oiled vegetation. Other spills in marshes that showed a net increase in biomass from light oiling included a pipeline spill of South Louisiana crude that affected *Phragmites australis* in the Mississippi River delta (Lin et al. 1999) and a spill of No. 6 fuel oil that affected *S. alterniflora* marsh in the Potomac River (Krebs and Tanner 1981). Although the mechanism by which oil stimulates plant growth is uncertain, Lin et al. (1999) hypothesized that oil in marsh soils may increase microbial N-fixation or shift competitive interactions among species. Increases in *S. alterniflora* shoot density were observed in heavily oiled marshes following the *Deepwater Horizon* crude oil spill; however, corresponding increases in plant cover and aboveground biomass did not occur, indicating possible overall declines in plant health (Zengel et al. 2022a).

There are few studies of the impacts of heavy refined oils in freshwater environments. Burk (1977) studied a heavy fuel oil spill in a freshwater marsh in February (see Appendix C), documenting high mortality of annual species, and impacts that lasted at least four years. Perennial species were less affected. Alexander et al. (1981) found that oiled/cut *Typha* spp. along the St. Lawrence River grew taller but didn't flower the first year after the spill, but had normal growth and flowering by the second growing season. Study of the spill of Bunker C into Lake Wabamun in Alberta for two growing seasons indicated that oil exposure during the late growing season in August 2005 and the winter senescent period did not cause large-scale effects on the summer regrowth in 2006 and 2007 for the reed-bed communities, except for some treated sites (Wernick et al. 2009). Spills in freshwater environments, where water-level fluctuations are seasonal rather than daily, have a lower risk of contamination of the marsh soils, unless the oil sinks. Thus, there is potential for quick recovery rates, particularly in rivers that have the benefit of continuous water flow to speed natural removal processes. Large lakes can have significant wave energy; small ponds generally do not.

There have been several field or greenhouse oiling experiments using heavy fuel oil. Alexander and Webb (1985) included a No. 6 fuel oil in their field oiling experiments that were mentioned previously and summarized in Appendices A-C. There were slight impacts to vegetation for the 1.5 L/m^2 partial and 2 L/m^2 entire plant applications in May, but only for months 1 and 5 after oiling. By month 12, the oiled plants were no different than the unoiled controls.

Based on the published studies and personal observations of the authors at many spills of heavy refined products in marshes, long-term impacts (>2 years) are likely to occur for the following conditions:

1) There is chronic re-oiling;
2) The marsh soils are heavily oiled, often by thick layers on the surface, or by subsurface oiling such as via animal burrows or other secondary porosity;
3) The entire plant surface is covered with oil during the growing season; or
4) There has been aggressive treatment that causes damage to roots and mixes oil into the soils.

Relatively short recovery periods (1-2 growing seasons) are likely to occur when:

1) Oiling degree is light;
2) Oiling occurs in the fall or winter when the plants are in senescence;
3) There is little to no contamination of the marsh soils; or
4) The oiled areas are exposed to waves or currents that speed natural removal rates.

The above points also apply to the coating and smothering effects of crude oil spills.

In the next sections, these and additional factors influencing the degree of impact of oiling of marsh vegetation are summarized in further detail.

Extent of Contamination of the Vegetation

As discussed in the previous section, the extent of oil on the vegetation is an important factor in determining the initial impact on vegetation. Although we know that there are important differences between field spills and greenhouse experiments, the greenhouse studies do provide good control to demonstrate this effect. Review of Appendices A-C shows that:

1) When the entire plant leaves and stems and the soil surface are covered with 1.5-2 L/m^2 of light refined oil, there is usually 100% mortality of the aboveground vegetation and sometimes high mortality of the entire plant;
2) Similar coverage and loading by heavy refined oils and crude oils in some greenhouse experiments result only in a slight decrease in aboveground biomass for a few months; however, this varies by species and similar coverage with higher oil loadings can result in high mortality, including whole plant death; and
3) At spills where at least the upper one-third of the aboveground vegetation remains unoiled without heavy oil loading on or in the soils, the plants tend to have high survival rates.

Thus, there is a general dose-response relationship in terms of the degree of oiling of the vegetation, with emphasis on the leaves versus the stems. The leaves are responsible for respiration, transfer of oxygen to the roots, photosynthesis, and, in some cases, salt extrusion. Light oils exert a chemical toxicity, damaging the plant cells and their functions. Heavy oils are thought to exert a physical toxic effect through coating and smothering. Both mechanisms of toxicity are a function of the amount of oil coverage of the leaves. Of course, the degree of oiling of the marsh soils and the exposure of belowground plants parts to oil are also important (discussed below).

Degree of Contamination of the Marsh Soils

One of the concerns about manual or mechanical treatment in oiled marshes is the risk of mixing oil into the marsh soils, which can increase the likelihood of further damage. A similar concern applies when oil penetrates or becomes buried in marsh soils. Marsh plants have variable degrees of tolerance to oil in their soils. Greenhouse experiments allow for controlled comparisons of plant responses to various degrees of oiling. Figure 2-1 shows that there is a dose-response relationship for sprigs of *S. alterniflora* exposed to different amounts of No. 2 fuel oil mixed homogenously into marsh soils in pots for three months. Starting around 29 milligrams/gram (mg/g; 29,000 parts per million [ppm]), oil exposure starts to have detrimental effects on belowground biomass; aboveground biomass effects start at exposure to 57 mg/g. Lin and Mendelssohn (2008) also exposed *S. alterniflora* to weathered South Louisiana crude at six doses for 12 months, with various measures of plant health significantly lower at 320 mg/g and 640 mg/g. No plants survived exposure to 800 mg/g. These studies also support the conclusion that No. 2 fuel oil is more toxic to *S. alterniflora* than South Louisiana crude oils (and likely many other similar crude oils). Lin and Mendelssohn (2009) did similar studies with *Juncus roemerianus* exposed to weathered diesel for twelve months, with detrimental impacts to biomass occurring at 80 mg/g.

These thresholds of oil contamination from greenhouse experiments are higher than what is normally found in the field. Levels of No. 2 fuel oil in marsh soils after the *Florida* spill in Buzzards Bay, which caused extensive plant mortality, were 0.45-0.59 mg/g right after the spill and 0.76-1.80 mg/g three months later (Sanders et al. 1980). At the *Bouchard 65* spill of No. 2 fuel oil in 1974 in Buzzards Bay, which also caused extensive marsh mortality and significant erosion, soil concentrations measured right after the spill were 11.4 and 20.6 mg/g in the top 6 centimeters (cm) (Teal et al. 1978). At the 1990 Exxon Bayway spill of No. 2 fuel oil in the Arthur Kill, New York, initial oil concentrations in the soils where marshes were killed were a mean of 6.4 mg/g right after the spill, a mean of 7.5 mg/g three years later, and a mean of 8.0 mg/g five years later in areas still denuded of vegetation (Bergen et al. 2000).

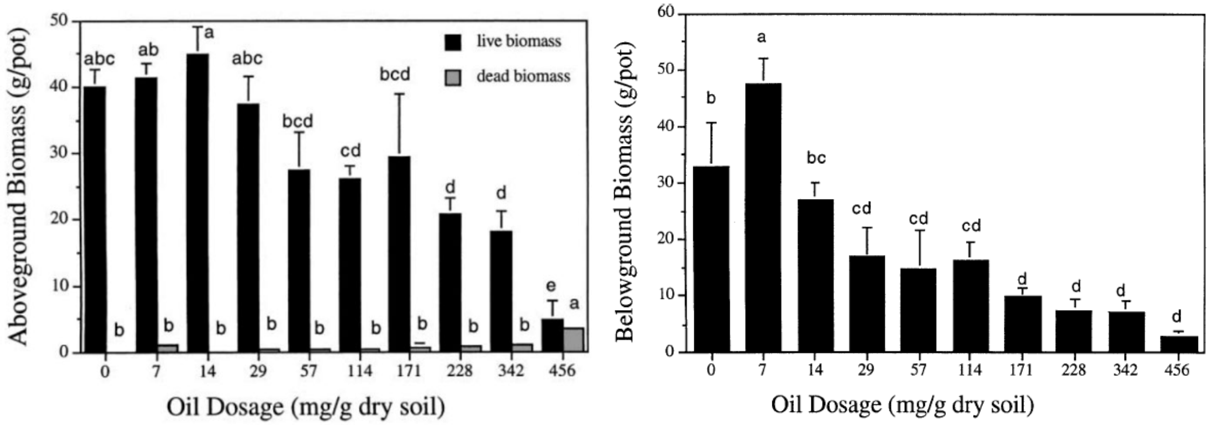

Figure 2-1. Effect of No. 2 fuel oil on the aboveground (left) and belowground (right) biomass of *S. alterniflora* three months after transplantation into soils mixed with different levels of oil. Values are means with standard errors (n=3). Means with the same letter are not significantly different. There is clearly a dose-response relationship (Lin et al. 2002b).

For crude and heavy refined products, the results are more variable. When planting marsh sprigs in an oil-impacted marsh, No. 6 fuel oil in soils at concentrations less than 2 mg/g had no effect on *S. alterniflora*, 2-10 mg/g had increasing effects, and greater than 10 mg/g resulted in plant mortality (Krebs and Tanner 1981). A light crude oil in the soil greater than 10.5 mg/g reduced live stem density of *S. alterniflora* and led to long-term impacts (Alexander and Webb 1987). The application of up to 8 L/m^2 of S. Louisiana crude oil to field plots enclosed by metal cylinders did not adversely affect *S. alterniflora* after three months, though the TPH levels in the soils at the end of the study were 40 mg/g (DeLaune et al. 1979).

Four spills stand out in terms of the persistence of a thick layer of oil on the marsh surface that affected recovery of the vegetation: a small spill in 1969 in Wales where a 5-cm thick oil layer on the marsh surface was not removed and the vegetation took 15 years to recover (Baker et al. 1993); the 1974 T/V *Metula* where 5-10 cm of thick emulsified oil covered the marsh surface and recovery was estimated to take decades (Figure 2-2); the 1991 Gulf War oil spill in the Arabian Gulf where thick and deeply penetrated oil resulted in extensive mortality (Barth 2002; Research Planning Inc. 2003; Höpner and Al-Shaikh 2008); and the 2010 *Deepwater Horizon* where mousse several centimeters thick was trapped under a layer of oiled vegetation mats (Zengel et al. 2015; see case study in Chapter 4). In fact, it was the lessons learned from the three earlier spills that led to the decision to use intensive treatment methods for the marshes with thick oil residues from the *Deepwater Horizon* spill.

The differences between greenhouse experiments and spills might be related to how the oil penetrates the marsh soils during a spill. Spilled oil is not uniform in its distribution with depth; it often penetrates root cavities and burrows, forming pockets of very high oil loading and areas of clean sediment, particularly for viscous oils. Depending on the soil type, oil properties, and oil behavior over time, plant tissues will be exposed to widely varying oil concentrations for similar oil loading on the surface. Collecting a representative sample of such variable oil exposures is difficult, thus the range in measurements of how much oil causes different effects.

Exposure to Currents and Waves

The degree of exposure of a shoreline to mechanical energy generated by waves and currents is a core concept in shoreline sensitivity and the persistence of stranded oil, as evidenced in the Environmental Sensitivity Index shoreline classification scale (NOAA 2010). The residence time of oil on a shoreline increases as the energy of waves and currents decrease. Though marshes occur in low energy environments, there are still relative differences among the physical settings that are important to consider in determining the rate of natural removal by physical processes. For example, the T/V *Metula* in the Strait of Magellan heavily oiled 5-10 ha of tidal salt marsh, with spring high tides stranding thick layers of oil on the high marsh surface. In this cold, arid climate, there are no physical processes to assist in oil removal, thus the oil is predicted to persist for decades (Figure 2-2). In contrast, the heavily oiled marsh along the Delaware River from the T/V *Grand Eagle*, exposed to strong riverine and tidal currents, and boat wakes, recovered within two years (Figure 2-3 A and B).

There are many examples of the importance of waves and currents in speeding natural removal of oil on marshes. At the 2010 *Deepwater Horizon* oil spill, at least 1,105 km of marsh shorelines were oiled; however, shoreline treatment was approved for only a small portion of this area (Michel et al. 2013; Zengel and Michel 2013; Nixon et al. 2016). One year later, based on ongoing surveys, there were approximately 200 km of visibly oiled marsh remaining. The bottom row of photographs in Figure 2-3 shows one lightly oiled area in Louisiana where the oil was removed by wave action over a period of a few weeks.

Time of Year of the Spill

Observations during experimental and actual spills have shown that the time of year of oiling of marsh vegetation is an important factor in the potential for impacts and the rate of recovery. In fact, Baker (1971) was the first to report that oiling outside of the growing season was less damaging. Several researchers have suggested why seasonality is so important (Mendelssohn et al. 1995; Webb 1996; Pezeshki et al. 2000). When plants are growing, they are physiologically very active, thus if oiling interrupts these physiological functions, plant health can be affected. Damage to leaf stomata, either by coating by heavier oils or tissue damage by lighter oils, can reduce transpiration, which can lead to overheating and death of the aboveground vegetation. Oil coating can also reduce oxygen transport to the roots, which can kill the belowground vegetation. Oil can reduce photosynthetic rates, which can slow growth and affect plant survival.

In contrast, it is clear that marshes that are oiled at the start of or during dormancy, when the aboveground vegetation growth has slowed or naturally died back, have a much greater potential for recovery. It makes sense that oiling of senescent vegetation would have less physiological stress on the plant. Figure 2-4 shows a *S. alterniflora* marsh that was heavily oiled in late September 1996 during the T/V *Julie N* spill of an IFO 380, compared with the next summer. The vegetation fully recovered in one growing season, in spite of the very heavy oiling of the vegetation, with only passive recovery of oil using sorbents.

Figure 2-2. Examples of long-term persistent oiling in highly sheltered marshes. Punta Espora, Chile marsh that was heavily oiled as a result of the T/V *Metula* spill in 1974. A) Oiled marsh in January 1976. B) Same area in January 1981. The oil stranded on the high marsh platform where it was isolated from physical removal processes. The oil is expected to persist for many decades. C and D) In 1995, the marsh surface has been covered by a thin layer of silt; however, the thick layer of oil has peristed for 21 years. Photo credit: Erich Gundlach.

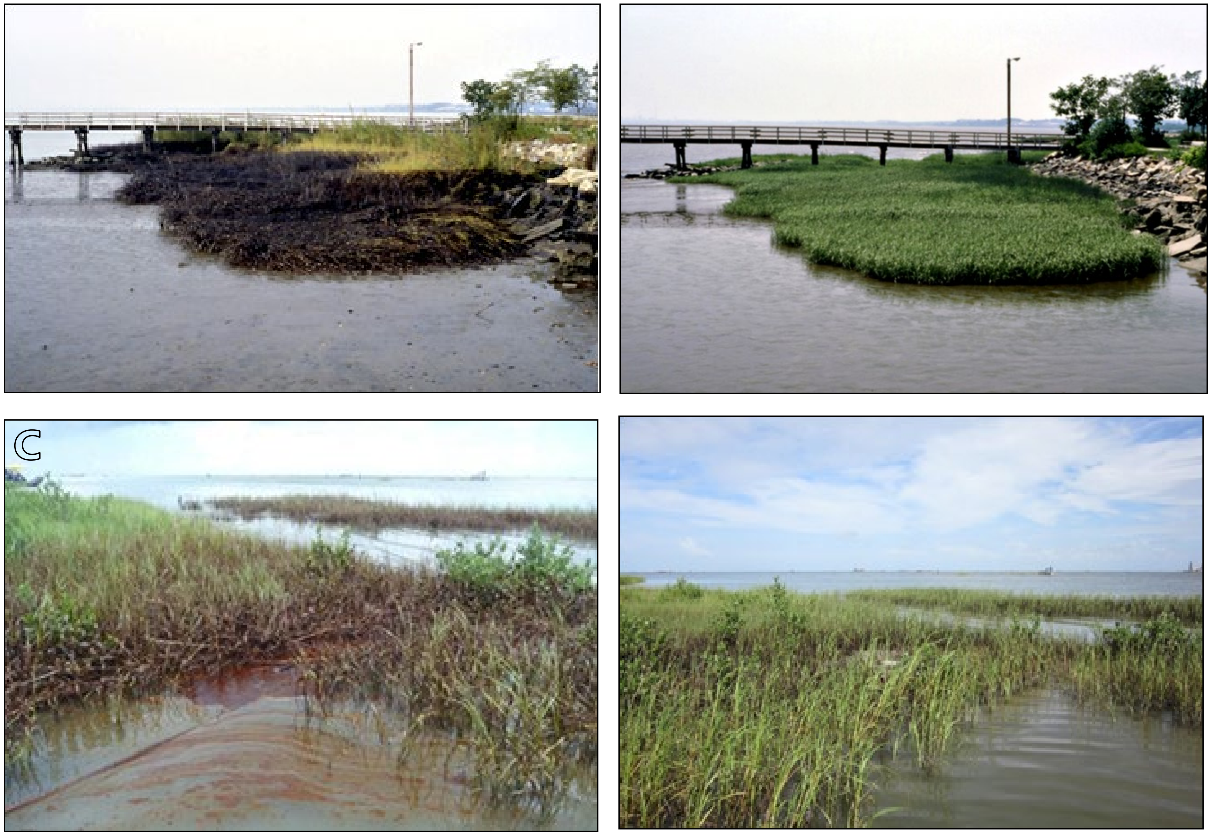

Figure 2-3. Examples of the role of natural removal processes for relatively exposed marshes. Top Row: *Grand Eagle* spill in the Delaware River. A) 1984; B) 1986. Strong river currents and boat wakes were very effective at natural oil removal. Photo credit: Tom Ballou. Bottom Row: *Deepwater Horizon* oil spill. C) Lightly oiled Louisana salt marsh on 3 July 2010; D) Same area on 27 July 2010. Photo credit: Missy Kroninger.

Figure 2-4. Heavily oiled *S. patens* marsh during the T/V *Julie N* spill of an IFO 380 in Portland, Maine in October 1996 (left) and July 1997 (right), showing the importance of season in how plants respond to oil exposure. Oiling in fall, when the plants are in senescence, has the lowest potential for impacting the vegetation. Photo credit: Jacqueline Michel.

Species Sensitivity

Marsh plants vary in their sensitivity by species and even by variety and ecotype within species (Lin and Mendelssohn 1996; Pezeshki et al. 2000; DeLaune et al. 2003; Lin and Mendelssohn 2012; Judy et al. 2014; Pezeshki and DeLaune 2015; Lin et al. 2016; Zengel et al. 2022a). Based on various greenhouse and field studies (cited above), the following species can be generally ranked from least to most sensitive to oiling (modified from graphic in Pezeshki and DeLaune 2015):

Least Sensitive →			→ **Most Sensitive**
Sagittaria lancifolia (bulltongue arrowhead)	*Spartina alterniflora* (smooth cordgrass)	*Spartina patens* (saltmeadow cordgrass)	*Juncus roemerianus* (needlegrass rush)
Phragmites australis (common reed)	*Distichlis spicata* (saltgrass)		
Typha latifolia (broadleaf cattail)	*Panicum hemitomon* (maidencane)		
Schoenoplectus americanus *(chairmaker's bulrush)*			

The above rankings should be considered cautiously, as relative species sensitivities can vary according to oiling and habitat conditions, including oil type, degree of oiling, marsh type, hydrology, soil organic content, time of year, greenhouse versus field settings, and even among similar studies. Relative sensitivities may differ from the above during individual spill events.

Sensitivity among species may be controlled by the depth and size of the rhizomes, with deeper rhizomes less likely to be exposed to oil on the surface and larger rhizomes having more food storage and ability to survive short-term effects on photosynthesis and other metabolic processes. It may also be a function of the properties of the soils the plants grow in. Oil tends to accumulate and persist in soils with high organic matter content, depending on the water levels when oil is present.

It has generally been found that annuals are more sensitive to oil than perennials. Annuals must grow every year from seed, so they would be more susceptible than plants that regrow from an existing root network. However, if there is a nearby source of seeds, annuals are often the first to recolonize a heavily oiled marsh, and so may recover more quickly than perennials. As the surface oil weathers, new seeds can germinate in the cracks in the oil layer. Once some vegetation takes root, it speeds the overall rate of recovery (see the case study of the *Amoco Cadiz* spill in Chapter 4). In contrast, perennial plants usually recover from the spread of roots from live plants around a heavily impacted site, which can be relatively slow.

One result of the different sensitivities of plant species is that oiling can cause temporary changes in the plant species composition of a marsh because of dieback of more sensitive species, expansion or establishment of more tolerant species, and differences in recruitment and recovery rates among species. However, eventually the normal species distribution returns if other habitat factors have not changed (such as a change in the elevation of the marsh). This effect has been seen at spills and in greenhouse experiments, mostly in brackish and freshwater marshes because they can have a more diverse mix of species present. Salt marshes are usually dominated by one species, or a distinct zonation of species, that can best survive and compete given the salinity regime and tidal elevation. Even so, shifts in plant species composition have been observed for heavily oiled salt marshes. In some cases, plant species composition can take years to recover.

Impacts of Oil on Marsh Fauna

There are few studies of the impacts of oil on the fauna associated with marshes. Many of the available studies focus on epifauna, such as intertidal burrowing crabs, periwinkle snails, and mussels. High rates of mortality for fiddler crabs have been documented after several oil spills. After the *Florida* No. 2 fuel oil spill in Buzzards Bay, Krebs and Burns (1978) and Culbertson et al. (2007) documented a variety of long-term toxic effects on fiddler crabs, ongoing nearly 40 years after the spill in areas with subsurface oiling.

Fiddler crab impacts were also reported for the Exxon Bayway spill of No. 2 fuel oil in the Arthur Kill (Burger 1994), a crude oil spill in Nigeria (Snowden and Ekweozor 1987), the *Deepwater Horizon* crude oil spill in Louisiana (Zengel et al. 2016a), and a No. 6 fuel oil spill in New Jersey (Dibner 1978). Oil can affect crabs in several ways: 1) acute and chronic mortality from the toxic components of the oil; 2) physical smothering by heavier oils; and 3) creation of physical barriers to access to the marsh surface and subsurface sediments such as thick oil layers, viscous oils, and algal mats. Massive mortality of intertidal burrowing crabs occurred as a result of the largest marine oil spill in history, the Gulf War spill in the Arabian Gulf, and the crabs have been a key part of the overall recovery of intertidal communities because of their prodigious burrowing which speeds oil degradation (Barth 2007). In fact, the large remediation and restoration projects along the Saudi Arabian coast are focusing on removal of the physical barriers to crab recruitment (Hale et al. 2011).

Marsh periwinkle snails are also very susceptible to oiling impacts, both from direct exposure but also because they are closely associated with the marsh substrate and emergent vegetation in the marsh, typically *S. alterniflora*. While vertical movement up and down cordgrass stems for feeding, predator avoidance, and regulation of temperature is frequent, marsh periwinkles rarely move laterally more than a few meters (Vaughn and Fisher 1992). Oil spills and experimental studies have observed high mortality of periwinkles immediately after a spill, followed by gradual increases in numbers over months or years as the vegetation recovers (Hershener and Moore 1977; Hershener and Lake 1980; Krebs and Tanner 1981; Lee et al. 1981; Zengel et al. 2016b, 2017; Garner et al. 2017; Deis et al. 2020). In some cases, periwinkles may lag vegetation recovery, resulting in delayed recovery for years to a decade or longer.

Ribbed mussels can be important to the survival of *S. alterniflora*, particularly along waterways with high wave energy and heavy boat traffic and wakes, by binding the root mat together, effectively stabilizing the substrate and strengthening the plant and the entire marsh against physical disturbance and erosion (Bertness 1984). Ribbed mussels are also important filter feeders, playing a key role in the food web and in the cycling of carbon, nutrients, and minerals through the salt marsh ecosystem. Several of the spills listed in Appendices A-C include cases where high mortality of ribbed mussels was noted, particularly for light refined oils. Ribbed mussels are also susceptible to smothering from oil or inability to recruit due to chronic toxicity (see the case history for the T/B *Florida* spill in Chapter 4). Similar observations on the role of nearshore oysters along marsh shorelines and oil spill impacts have also been reported (Powers et al. 2017).

The *Deepwater Horizon* spill provided several related studies on marsh infauna, those small macroinvertebrates and meiofauna including polychaetes, amphipods, bivalves, copepods and nematodes, among many others, that live in intertidal marsh soils. Marsh infauna density and species diversity were impacted in lightly to heavily oiled marshes, with near 100% mortality in heavily oiled areas (Fleeger et al. 2015; 2018; 2019; 2020; 2022). Total meiofauna densities began to recover within about 2 years and total macroinfauna densities within about 4.5 years in heavily oiled sites, often in conjunction with recovering marsh vegetation. However, several infauna species, including the dominant marsh polychaete *Manayunkia aestuarina*, as well as overall infauna species composition, did not recover by 6.5 years post-spill, perhaps related to slower recovery of belowground plant biomass and soil characteristics. Full infauna recovery was predicted to take up to 10 years in moderately oiled sites and longer for heavily oiled sites.

The *Deepwater Horizon* spill also provided some of the only available information on oil spill impacts to marsh insects (e.g., planthoppers, grasshoppers, ants, midges, flies) and spiders. For insects and spiders in unoiled or lightly oiled areas just inland from heavily oiled marshes indirect impacts were observed across several feeding guilds, including 25–50% reductions in density across different groups, although recovery mostly occurred within one year (McCall and Pennings 2012; Pennings et al. 2014). Longer-term direct impacts to insects were reported in more heavily oiled marsh areas with recovery exceeding four years (Bam et al. 2018). Greenhead horse flies (*Tabanus nigrovittatus*), which have both intertidal and flighted terrestrial life stages, suffered a severe population crash in oiled areas, due to impacts to their infaunal larvae, which are predators in marsh soils, as well as to flighted adults (Husseneder et al. 2016). Horse fly populations were showing signs of recovery at 5–6 years post spill through adult immigration and as larval habitats were recovering, including recovery of their infaunal prey sources (Husseneder et al. 2018).

Studies of resident Gulf killifish (*Fundulus grandis*) in marsh habitats and in laboratory studies with oiled sediments affected by the *Deepwater Horizon* spill showed a wide range of sublethal responses, including development abnormalities in gills, liver, head, kidney, and intestine of adult and larval fish; cardiovascular defects in embryonic fish; and delayed hatching, overall reduced hatching success, smaller size at hatching, and edemas (Whitehead et al. 2011; Dubansky et al. 2013). Behavioral effects such as reduced foraging rates and reduced avoidance of oiled sediments were also observed (Martin et al. 2020; McDonald et al. 2022). Killifish have small home ranges and high site fidelity, making them particularly sensitive to impacts from persistent oil exposures. However, population and community level effects on marsh fishes following the *Deepwater Horizon* spill were generally not observed, although study timing, location, and various other factors may have contributed to these findings (Moody et al. 2013; Fodrie et al. 2014; Able et al. 2015).

Summary and Response Implications

The body of literature on oil toxicity and impacts to marshes is extensive and provides a range of results from which we can extract guidance to assist planning for or responding to oil spills.

- When a spill threatens a shoreline, marshes are likely to become oiled because they occur in the upper intertidal zone where the oil usually strands. The degree of impact is very closely correlated with the degree of oiling. Therefore, response actions that minimize the amount of oil that reaches the shoreline will reduce the degree of impact to these sensitive and productive habitats.
- Spills of light refined oils can result in high mortality of marsh vegetation and biota, but only where large amounts of oil strand on the shoreline, such as large spills in inland waterbodies, small spills in small waterbodies, or spills directly into marshes. In most offshore spills, light refined oils spread, disperse, and evaporate to the point that the amount of oil that reaches the marsh is not enough to cause large-scale effects.
- Crude oils and heavy refined oils that coat the entire plant, and particularly the leaves, will have the greatest potential impacts, even more so if the soils are also oiled. Oiling of only the stems or parts of the stems often results in limited mortality. If only portions of the aboveground vegetation are oiled, regrowth is likely during the next growing season, particularly for oiling of the marsh fringe where natural removal processes are relatively fast.
- Spills in the marsh interior are likely to result in thicker oil residues, higher impacts (partially because of the lack of weathering before contact with the marsh), and slower natural removal rates. Thus, these kinds of spills often require intensive removal actions.
- Impacts are more persistent when oil penetrates into the marsh soils. Persistence increases with deeper oil penetration, soils high in organic matter, and sites that are sheltered from natural removal processes.
- Vegetation recovery will occur more quickly for spills of any type of oil during the non-growing season, compared to a spill during the growing season.
- Although there are some indications of different sensitivities among species, the specific spill conditions are the most important factors in determining impacts.
- Annuals are more likely to be affected compared to perennials; however, they often are the first to recruit to oiled sites and can lead the recovery process.
- Thick oil layers on the marsh surface are known to cause long-term impacts to both vegetation and fauna; therefore, early removal actions can speed recovery, as long as oil removal is well planned and conducted with careful oversight.

There have been several summaries of the recovery rates for oiled marshes. Sell et al. (1995) compared the recovery rates of heavily oiled salt marshes for 17 spills and field experiments, showing that sometimes treatment resulted in more rapid recovery, and sometimes treatment slowed recovery. Hoff (1995), in her paper on "The Fine Line between Help and Hindrance" summarized recovery rates for 17 spills and field experiments (there were seven cases common to both summaries) and made similar observations.

Figure 2-5 shows a plot of the estimated "years to recovery" for 38 spills and field experiments for lightly to heavily oiled marshes (48 spill scenarios in total). For this update, marsh recovery rates from Michel and Rutherford (2014) have been updated with information from Michel (2021a, 2021b), specifically the marsh chapters from Latham and Zengel (2021a, 2021b). *Deepwater Horizon* updates were based on Zengel et al. (2022a). Note that for the Gulf War oil spill, those marshes that showed little or no recovery as of 2009 were treated during an extensive remediation and restoration program that started in 2011 and continues as of 2022, thereby shortening what would have been even longer recovery periods for the marshes, which were drastically impacted and include long-lived, slow-growing, woody perennial sub-shrubs.

The interpretations are similar to Sell et al. (1995) and Hoff (1995), as well as Mendelssohn et al. (2012), Michel and Rutherford (2014), and Pezeshki and DeLaune (2015), in that:

Recovery is longest for spills with the following conditions:

- Cold climate (e.g., *Metula*, *Arrow*, *Amoco Cadiz*)
- Sheltered settings (e.g., *Metula*, *Arrow*, Gulf War, Nairn pipeline, Mill River)
- Thick persistent oil on the marsh surface (e.g., *Metula*, *Amoco Cadiz*, Gulf War, *Deepwater Horizon, Arrow*)
- Light refined products with heavy loading (e.g., *Florida*, *Bouchard-65*, Exxon Bayway)
- Oil that penetrates, becomes mixed into, or buried in the marsh soils (*Florida*, *Bouchard-65*, Exxon Bayway, Gulf War, *Deepwater Horizon*)
- Repetitive, extended, or chronic re-oiling (*Deepwater Horizon*)
- Overly aggressive treatment (e.g., Aransas Pass, *Amoco Cadiz*, *Golden Robin*)

Recovery is shortest for spills with the following conditions:

- Warm climate (e.g., many but not all spills in Louisiana and Texas)
- Light to moderate or partial oiling of the aboveground vegetation only
- Spills in fall or winter (outside the growing season)
- Medium crude oils (with exceptions)
- Less-intensive or no treatment.

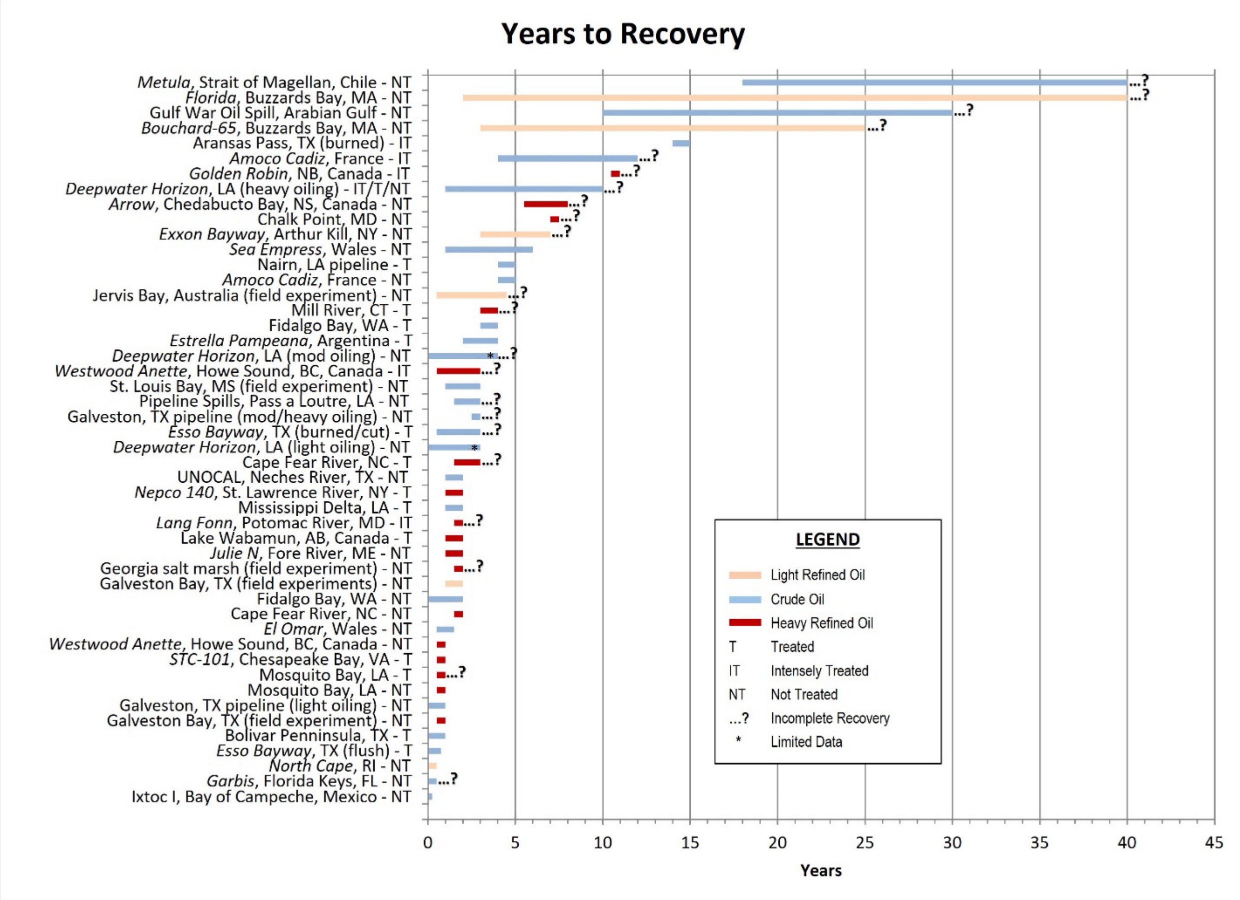

Figure 2-5. Years to recovery for spills and field experiments color-coded by oil type, shown from longest to shortest recovery times. Dots and question marks at the end of the horizontal bars indicate that recovery was incomplete or ongoing based on results of the most recent data.

It is interesting to note in Figure 2-5 that for roughly half of the spills shown, recovery occurred within 1-2 growing seasons, even in the absence of any treatment. Many smaller marsh spills that are not as widely reported or studied (and so do not appear in the table) would fit in this category. The decision to conduct treatment operations in oiled marshes needs to be based on the best understanding of the likely tradeoffs. Every spill is a unique combination of conditions that must be evaluated to determine if and how much of the oil must be removed, and the most effective but least damaging removal methods. In Chapter 3, we discuss guidelines on appropriate removal and treatment methods.

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CHAPTER 3. RESPONSE

Key Points

- Marshes are highly sensitive to oil and often are priority areas for protection.
- Winds and currents can carry spilled oil into marshes where the oil coats the soil surface, vegetation, and animals in the marsh.
- Dispersing or burning offshore can in some cases prevent or lessen impacts to coastal marshes during marine spills, though these response options are usually not appropriate for freshwater environments.
- Spill containment and cleanup techniques need to be carefully evaluated for the specific spill conditions, to minimize any additional impacts to marsh environments and associated fauna and speed overall recovery post spill.
- Often, multiple response options should be used in combination or succession.
- At some point in time, all treatment methods will become less effective and can potentially cause additional damage.

As detailed in the previous chapter, marshes are particularly sensitive to oil and should be priority areas for protection. However, it is difficult to protect extensive marshes even under ideal conditions, and the rapid transport of oil onshore often results in oiling of these sensitive habitats. Any oil removed during on-water response will reduce the amount of oil potentially reaching the shoreline. On-water response options to minimize oiling of wetlands discussed here include mechanical containment and recovery, offshore dispersant application, and offshore in situ burning.

Once oil reaches a marsh, the impact of oiling varies by oil type, degree of oiling, wetland type, weather, water levels, degree of exposure to waves and currents, and time of year. Cleanup options should be evaluated to determine whether the ultimate benefits from the response action outweigh any additional impacts occurring during their implementation. This chapter summarizes what is known about the environmental tradeoffs with different treatment options.

On-Water Response Options to Prevent Marsh Oiling

Mechanical Recovery

Mechanical containment and collection of spilled oil on water using equipment such as booms and skimmers are primary initial cleanup methods used at many spills. Experience has shown, though, that mechanical recovery alone usually cannot adequately deal with offshore spills. Weather and sea conditions, the nature of the oil, and other factors may limit the effectiveness of mechanical recovery.

Experience has shown that mechanical recovery rates greater than 20% are rare. In such cases, alternative open-water response techniques, such as dispersant application or in situ burning of oil on water, may reduce the risk that oil will reach shore and impact marshes and other sensitive intertidal and nearshore habitats.

Offshore Dispersant Application

Chemical dispersants are products applied to oil on the water surface in offshore areas to enhance formation of smaller oil droplets that are more readily mixed into the water column and dispersed by turbulence and currents. During and since the *Deepwater Horizon* oil spill, dispersants have also been considered as a response option to reduce the amount of oil reaching the surface during an offshore subsea release. Most oils physically disperse to some degree due to agitation created by wave action and ocean turbulence. Chemical dispersants enhance and speed up this natural dispersion process. Dispersing oil soon after release minimizes impacts to wildlife at the water surface (e.g., birds, sea turtles, and marine mammals) and reduces the amount of floating oil that may reach sensitive nearshore and shoreline habitats. If applied appropriately offshore, chemical dispersants can be an effective tool for protecting marshes and the habitat they provide. Tradeoffs among other resources at risk, such as potential effects of temporarily higher concentrations of oil in the water column on pelagic organisms and sedimentation of oil in sensitive benthic habitats such as deep water reefs, should be considered before dispersant use. In freshwater environments, there are additional concerns about mixing oil into the water column that would increase the risk of contamination of water intakes, and about the slower mixing and dilution rates and water volumes in most lakes, thus increasing concerns about impacts to aquatic resources. Furthermore, most current dispersant formulations are not all that effective in freshwater. Therefore, use of chemical dispersants is not likely to be considered appropriate during spills in freshwater environments.

Offshore In situ Burning

In situ burning is a response technique in which spilled oil is burned in-place. When used appropriately, in situ burning offshore can remove large quantities of oil quickly and efficiently with minimal logistical support. Like dispersants, in situ burning of offshore spills can help minimize impacts to wildlife at the water surface and reduce the amount of oil that reaches sensitive nearshore and shoreline habitats. A potential disadvantage of open-water in situ burning is that a small percentage of the original oil volume may remain as a taffy-like residue after the burn. Floating residue can be collected, but residues that sink or escape collection and move inshore could potentially contaminate nearshore benthic habitats. Burning can also affect air quality.

Response Options for Oiled Marshes

When marshes are oiled, selection of the best response option(s) is very important. Table 3-1 is an updated version of the matrix for salt to brackish marshes from the NOAA (2010) *Characteristic Coastal Habitats: Choosing Spill Response Alternatives*. It ranks response options for shoreline cleanup in marshes for different oil types considering both the impact of the cleanup method and its effectiveness at oil removal. This matrix was developed for general oil spill scenarios and should be considered only as a starting point when evaluating potential marsh response alternatives. The matrix can be updated for the specific circumstances of individual spills. For instance, Henry et al. (2003) developed a modified matrix for two oil spills in floating marshes in Louisiana.

Table 3-1. Recommendations for response options in oiled marshes by oil group (modified from NOAA 2010).

Oil Group Descriptions

- I – Gasoline products
- II – Diesel-like products and light crudes
- III – Medium grade crudes and intermediate products
- IV – Heavy crudes and residual products

The following categories are used to compare the relative environmental impact of each response method in the specific environment and habitat for each oil type. The codes in each table mean:

- A = The least adverse habitat impact.
- B = Some adverse habitat impact.
- C = Significant adverse habitat impact.
- D = The most adverse habitat impact.
- I = Insufficient information – impact or effectiveness of the method could not be evaluated.
- – = Not applicable.

Response Method	Oil Group I	II	III	IV
Natural Recovery	A	A	B	B
Barriers/Berms	B	B	B	B
Manual Oil Removal/Cleaning	D	C	B	B
Mechanical Oil Removal	D	D	C	C
Sorbents	–	A	A	B
Vacuum	–	B	B	B
Debris Removal	–	B	B	B
Sediment Reworking/Tilling	D	D	D	D
Vegetation Cutting/Removal	D	D	C	C
Flooding (deluge)	B	B	B	B
Low-pressure, Ambient-water Flushing	B	B	B	B
Shoreline Cleaning Agents	–	–	B	B
Nutrient Enrichment	–	B	B	C
Natural Microbe Seeding	–	I	I	I
In situ Burning	–	B	B	B

In this section, the effectiveness and likely impacts of these response options are discussed. It is important to note that multiple response options may be used in combination or succession, depending on the oiling conditions.

Natural Recovery

There are many spills in marshes where the decision is made to allow natural recovery to proceed without any active cleanup, because active cleanup would cause more harm than benefit to the habitat and the animals using that habitat. Nearly all types of active cleanup will include some habitat damage or disturbance whether it is from the type of equipment used, the way it is used, or the mere presence of the cleanup workers disturbing wildlife or trampling the marsh. Typically, natural recovery is selected when:

- The spill is of a light oil that is expected to naturally evaporate and break down rapidly. The toxic effects of light refined products such as diesel and jet fuels occur quickly, and attempts to remove the oil could cause more damage.
- The impact area is small.
- The oil is mostly on the vegetation. As discussed in the section on oil impacts, it has been well documented that oil on vegetation will often weather to a non-sticky coating within weeks, and plants can often survive even heavy coating.
- The vegetation is in its dormant season. The aboveground vegetation for many species naturally dies back in the fall/winter and new vegetation emerges in spring. Therefore, the oiled vegetation will be replaced, and the oil is removed from the marsh by this process as well.
- The oiled marsh is exposed to waves and/or currents that speed the rate of oil weathering and removal.
- Key animals are not at risk, such as threatened or endangered species or large numbers of migratory waterfowl.
- Active cleanup methods are determined to be causing too much damage or are no longer effective and thus are terminated.

This last point is important; responders should continually reevaluate the shoreline response to make sure that approved methods are being properly implemented and are still effective and needed. Oils change properties as they weather, and methods that were initially very effective can become less effective over time.

Figure 3-1 shows time-series photographs of a spill where natural recovery was found to be very effective. When natural recovery is the preferred response option, it is still important to take action to contain any oil that is released from the marsh and prevent oiling of adjacent areas. Possible response options are discussed below in the order listed in Table 3-1.

Figure 3-1. T/V *Julie N* spill of IFO 380 into the Fore River, Portland Maine where natural recovery was very effective. (left) September 1996. (right) July 1997, one year later. Photo credits: Jacqueline Michel.

Barrier Methods

Barriers such as hard boom or filter fences can be used in an attempt to keep oil from stranding in the marsh. Booms float on water, so they need to be anchored or staked so that they do not foul on the intertidal zone during low tide or on the vegetation at high tide. This often happens anyway, so even booming can cause damage; it certainly causes disturbance because of the constant need for maintenance and replacement. Booms are particularly difficult to keep in place along shorelines exposed to waves and currents, and they should be removed when a large storm is predicted to affect the area. During the *Deepwater Horizon* spill, hard boom and sorbents were stranded along hundreds of kilometers of shoreline by large waves from an offshore storm (Zengel and Michel 2013). It took months of work by many special boom-removal teams to retrieve the stranded boom (Figure 3-2), and there was a massive effort to locate and remove orphan boom anchors. SCAT teams still found boom stranded in the marsh in early 2013, nearly three years after the spill. Therefore, responders need to carefully evaluate the effectiveness of placement of boom along extensive areas of marsh shoreline, particularly where exposed to waves. Improper booming can cause significant damage.

Filter fences have been placed along the marsh edge, with variable success. Numerous steel posts are necessary to keep them in place, and they often fail under wave action (Figure 3-3). Furthermore, they are very difficult to remove because the stakes get buried in mud, the cloth can get weighted down with mud, and debris tends to accumulate around them. Complete removal is important because the stakes can pose hazards to people and boats, particularly if the shoreline is eroding. Recording accurate GPS coordinates when such barriers are installed will aid in their location during removal actions. Based on experience during the *Deepwater Horizon* oil spill, such protection measures are not likely to be effective and pose significant difficulties during removal.

Figure 3-2. Top row: boom stranded on salt marshes (left) and *Phragmites* marsh (right) in Louisiana in July 2010 after the passage of two storms that generated waves and high water. Photo credit: Andy Graham. Bottom row: specialized boom retrieval teams removed the stranded boom using various techniques to minimize further damage to the marshes. Photo credit: *Deepwater Horizon* Response.

Figure 3-3. Shoreline barriers used during the *Deepwater Horizon* oil spill. Filter fences require many steel posts to keep them in place. Usually there is not enough time to deploy this type of barrier after a spill, they have limited effectiveness, and are difficult to remove. Also note the hard boom stranded on the marsh at left. Photo credit: Helen Chapman (left); Thomas Minter (right).

Manual and Debris Removal

Manual removal involves the use of hand tools and manual labor to remove thick accumulations of viscous oil and oiled debris from the marsh surface. Depending on location, vehicles such as marsh buggies and all-terrain vehicles may be used to haul workers and wastes. All work in soft sediments and in vegetated areas needs to be conducted using walking boards (planks of wood) to prevent damage. Trampling is very hard to avoid and often causes long-lasting damage, by driving the oil deep into the soils and physically damaging the vegetation and soils. There have been many spill responses in marshes where years later the main evidence of the spill is from the physical damage caused by foot traffic and vehicles used to transport workers and wastes. After a spill of Bunker C in a *Carex* marsh in British Columbia, where local stakeholders pushed for aggressive removal of the oil, Challenger et al. (2008) documented nearly complete vegetation mortality and increased and prolonged oil contamination of soils. However, with small teams, close supervision, and a clear understanding of the removal methods and adaptation over time, manual removal can be effective. During the *Deepwater Horizon* spill, much of the oiled marsh cleanup was conducted manually by teams that removed very heavily oiled wrack, oiled vegetation mats, and thick emulsified oil layers along at least 11 km of fringing marsh in Louisiana, with mainly positive results (Zengel and Michel 2013; Zengel et al. 2015; see the *Deepwater Horizon* case history in Chapter 4).

Mechanical Removal

Mechanical removal is seldom used because of the potential for extensive damage to the marsh soils. It is usually considered only under very heavy oiling conditions when rapid removal is of priority or where soft substrates limit manual removal. Two recent examples are the 2000 Chalk Point spill in Maryland and the 2010 *Deepwater Horizon* spill in Louisiana. The Chalk Point spill released 126,000 gallons of a mixture of No. 6 and No. 2 fuel oils from a pipeline break in the interior of a brackish marsh. A network of trenches was dug to improve low-pressure flushing efforts (Figure 3-4). The trenches were backfilled with clean material and bare areas successfully re-planted (Gundlach et al. 2003). Mechanical methods used during the *Deepwater Horizon* response included shallow floating barge and airboat platforms with long-reach hydraulic arms coupled with attachments for rakes, grapples, vegetation cutting devices, scrapers, and "squeegees" that involved only one spotter on the marsh to direct the operator on the boat (Zengel and Michel 2013; Zengel et al. 2015, 2021). Even with close supervision, mechanical methods had a greater chance of causing impacts compared to manual crews, and manual crews were still required for touch up after the mechanical treatments. For more discussion of mechanical removal methods and results, see the *Deepwater Horizon* case history in Chapter 4.

Figure 3-4. The extensive network of trenches dug during the Chalk Point oil spill in April 2000 to increase effectiveness of flushing of the mixture of No. 6 and No. 2 fuel oil that was released inside the marsh from a pipeline break. Extensive replanting was conducted and was very successful (Gundlach et al. 2003). Photo credit: Jacqueline Michel.

Sorbents

Even when natural recovery is the selected option, sorbents are often deployed to recover any oil released from the area. Sorbents are composed of materials that either adsorb oil on the surface or absorb oil into the pores of the material. There are many types: natural organic substances (e.g., peat, wood, cotton, straw, and "bagasse" – shredded plant residuals that remain after sugarcane harvesting and processing), synthetic organic substances (e.g., polypropylene, polyurethane), inorganic mineral substances (e.g., clay, vermiculite, diatomite), or a mixture of the three. The material may also be treated with oleophilic (oil-loving) and hydrophobic (water-hating) compounds to improve performance. They come in various forms: round sausage “boom,” snare, sweeps, pads, rolls, loose particulates, pillows, and socks. In marshes, sorbents are often used in the following manner:

1) On water, sorbent “boom” is deployed to passively recover oil being mobilized by waves and currents from the marsh. Care is needed during placement and removal to minimize the damages and disturbances previously described for hard booms used as barriers. Sorbents can generate excessive wastes so they should be removed when sheening reaches minimal amounts.
2) On the marsh surface, sorbent pads and snares can be used to pick up liquid or sticky oil. Figure 3-5 shows workers on walking boards (which can be planks of wood nailed together or sheets of plywood) using snares to recover thick oil from deep inside a marsh where there was no access for vacuum systems.
3) On the marsh surface and vegetation, loose organic sorbents can be spread on the surface and lightly raked into areas of liquid or sticky oil (making sure not to disturb the vegetation or marsh sediments) then removed for proper disposal (Figure 3-6). This application method requires cleanup crews to walk on the marsh surface, so walking boards are required.
4) On the marsh surface and vegetation, loose organic sorbents can be applied by hand or a small blower to provide a barrier to reduce the risk of oil contact exposure to wildlife in the marsh. For fringe oiling, the sorbents can be applied from shallow-draft boats, otherwise, walking boards will be required for foot traffic on the marsh surface. In the U.S., approval from the Regional Response Team is required for application of loose organic sorbents without removal.

Figure 3-5. Workers using snares on poles to remove thick oil floating on the water surface deep in the brackish marsh interior at the Chalk Point oil spill on the Patuxent River, Maryland in April 2000. Note the use of walking boards. Photo credit: Jacqueline Michel.

Figure 3-6. Use of loose organic sorbents during the *Deepwater Horizon* spill in Louisiana on 9 July 2011. (left) Crews used potato rakes (lower left) to mix the sorbent into thick oil on the marsh surface then removed it. (right) A final layer of sorbent was applied at the end of treatment and left in place to reduce wildlife contact with newly exposed residual oiling (Zengel and Michel 2013). Photo Credit: Eric Schneider.

Vacuuming

Vacuuming can be used to remove pooled or thick oil accumulations on the marsh surface, in depressions, and floating in channels. Vacuum equipment ranges from small, portable units to large suction devices mounted on barges adjacent to the marsh edge. Vacuuming is most often appropriate to use early in the response for medium and heavy oils, when the oil is still liquid and floating on the water surface. Weathered or viscous oils have to be concentrated using booms and “fed” into the nozzle. Operationally, it is important to minimize vacuuming of water, because of limited storage capability and the water may have to be treated prior to discharge. The biggest limitations are usually logistical; that is, how to get the vacuum system to where the oil is in the marsh under variable tide and wave conditions and in shallow water. Land-based operations are limited by the distance over which the hoses can be laid out between the oil to be treated and the storage tank, though it can be hundreds of meters with use of booster pumps. Care will be required to minimize trampling of soils and vegetation during handling of hoses and actual vacuuming of the oil. Workers also need to be careful to not gouge the surface of the marsh, removing marsh soils and inadvertently changing the marsh elevation with potential adverse effects to marsh vegetative and fauna communities. Another issue is that the oil will continue to spread into thinner layers, reducing the effectiveness of vacuuming, thus rapid identification and removal of areas of pooled oil are essential. Hoff et al. (1993) showed that careful use of vacuum and flushing by workers using walking boards removed the most oil and minimized damage to a *Salicornia virginica* marsh in Fidalgo Bay, Washington which was heavily oiled by a spill of Prudhoe Bay crude oil. By the second growing season, there was 100% plant cover in all but one small area.

Figure 3-7 shows the use of a small vacuum system to recover emulsified oil from a tidal channel during the 1997 Bayou Perot, Louisiana oil spill. Note the use of boom in a "tear-drop" configuration to concentrate the oil and minimize pickup of water. The oil was pumped into barrels on an airboat; when the barrels were full, another airboat brought an empty replacement and ferried the full barrel back to a barge in deeper water.

During the *Deepwater Horizon* spill, crews used vessel-based vacuuming to remove the thick emulsified oil adjacent to oiled marsh vegetation in the most heavily oiled areas in Louisiana (Zengel and Michel 2013). Though this method removed a lot of mostly floating oil initially, when used later in the response within the marsh, the hard nozzle gouged the marsh surface and removed some wetter marsh soils, creating holes that allowed the mousse to seep into the soil. Once it was determined to be no longer effective and was causing more harm than benefit, operations were terminated. This is an important point to be made: at some point in time, all treatment methods will become less effective and can potentially cause additional damage. Thus, it is important to monitor operations to make sure that each method is still effective.

Figure 3-7. Vacuuming of thick oil from the water surface in a marsh channel, Bayou Perot, Louisiana in February 1997. Photo credit: Jacqueline Michel.

Vegetation Cutting

Cutting of oiled vegetation is considered for several reasons:

- To reduce contact hazards with wildlife, particularly birds and small fur-bearing mammals associated with the marsh;
- To speed the recovery of the marsh;
- To gain access to oil trapped by vegetation on the marsh surface or in thick vegetation; and
- For aesthetic reasons in public areas of high visibility.

Cutting methods include weed trimmers, power hedge trimmers, and floating mechanical reed cutters.

Zengel and Michel (1996) reviewed 22 spills and experiments where cutting was used as a treatment method and generated a tabular summary of each study. Figure 3-8 shows time-series photography of some of these cases. Ten other studies have been identified since then:

- A field experiment in Brazil where both cut and uncut *Spartina alterniflora* marshes oiled with a medium fuel oil recovered within six months (Wolinski et al. 2011);
- A small-scale field test of cutting of *Spartina foliosa* oiled by an intermediate fuel oil in Humbolt Bay, California that was revisited one and two growing seasons later showing the cut areas were slightly impacted versus natural recovery (Lesh and Jocums 1999);
- Cutting *Phragmites* to gain access to the marsh interior for flushing and floating oil recovery following small crude oil spills in Louisiana showed better plant recovery versus untreated areas (Lin et al. 1999; and photographs in Figure 3-9);
- Cut bulrushes after a spill of Bunker C into Lake Wabamun, Alberta, Canada recovered more slowly compared to uncut areas (Wernick et al. 2009);
- Cutting *Carex lyngbeyei* and *Eleocharis palustris* in an estuarine marsh after a Bunker C spill in British Columbia, Canada had no apparent impact positive or negative on vegetation recovery; however, where trampling occurred, oil persistence was prolonged and vegetation recovery reduced (Challenger et al. 2008);
- *Typha* that was cut during the spill of Bunker C from the barge *Nepco-140* in the St. Lawrence River grew taller but didn't flower the first growing season, but was normal the second growing season (Alexander et al. 1981);
- Cutting of a freshwater marsh in Puerto Rico dominated by *Paspalum*, *Urochloa, Cyperus*, and *Typha domingensis* after a No. 6 fuel oil spill resulted in foot trampling and mixing of oil into the soils; however, vegetation recovery occurred within ~1-2 years; uncut areas persisted or recovered similarly (Zengel et al. 2001);

Figure 3-8. Vegetation cutting time series. Top Row: The Cape Fear River, North Carolina spill of a No. 6 fuel oil where the vegetation was cut in May 1985 A). Two years later, the cut vegetation did not recover B). Photo credit: Research Planning, Inc. Bottom Row: The *Grand Eagle* spill of a medium crude oil into the Delaware River in summer 1985 that was cut C) but the vegetation recovered within two years D). Photo credit: Tom Ballou.

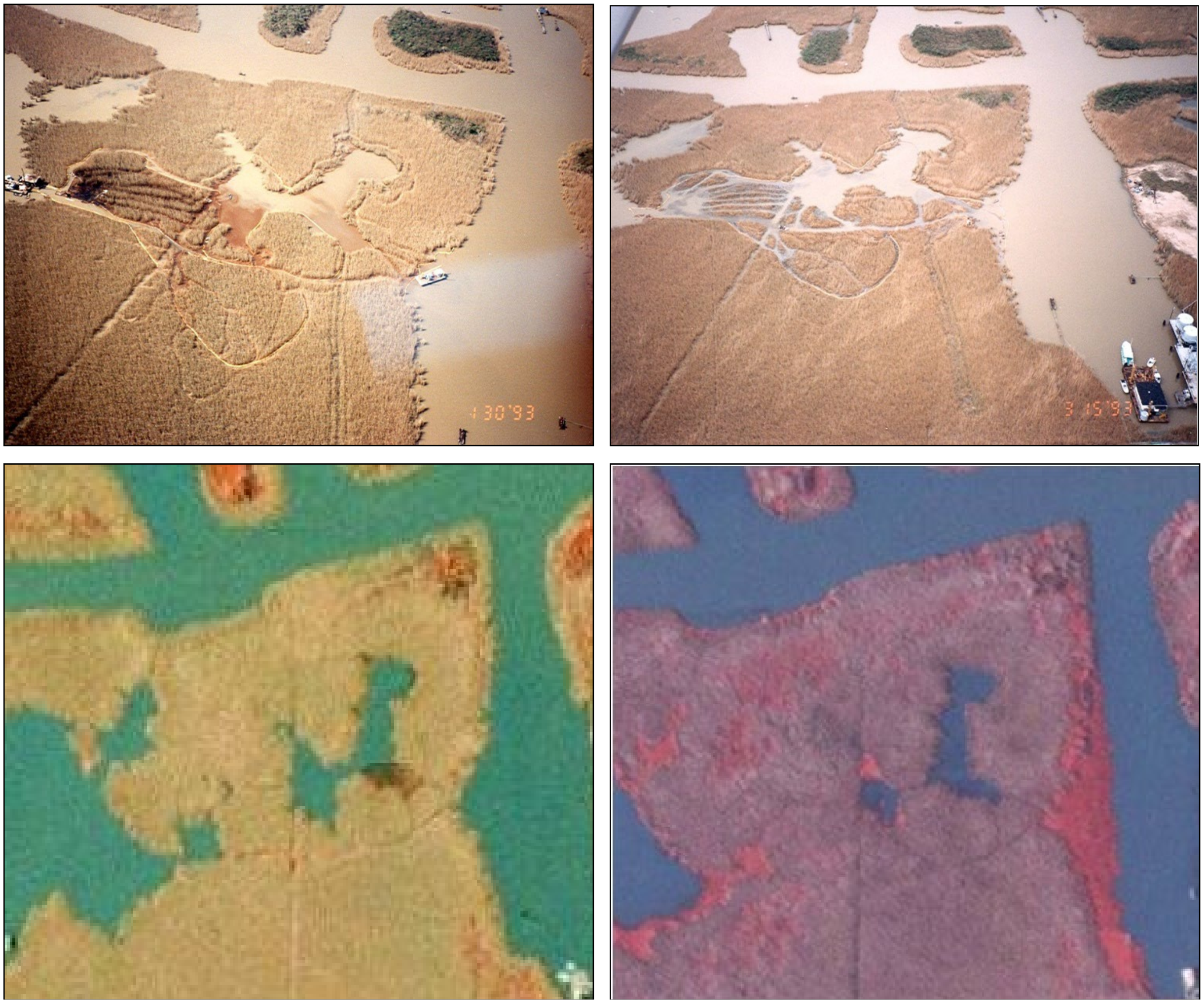

Figure 3-9. Time-series photographs of a spill in the Mississippi River birdsfoot delta, Louisiana in January 1993 where cutting of *Phragmites* was used to gain access to the marsh interior where the oil was up to 7 cm thick. The oblique photographs were taken in 1993 before A) and after cleanup B); note the multiple paths cut to access the oil. The vertical images were taken five C) and nine D) years later, showing good vegetative recovery in five years. Photo credit: Dwight Bradshaw.

- *Spartina alterniflora* cutting during an oil spill bioremediation field experiment with a medium crude oil in a salt marsh in Nova Scotia, Canada resulted in the suppression of plant recovery compared to no treatment or nutrient additions without cutting; natural recovery was considered the best approach (Lee et al. 2003);
- Cutting of *Panicum hemitomon* floating marsh during two crude oil spills in Louisiana was conducted on a limited basis for flowline repair and to create sumps for oil removal, which was marginally effective; further consideration of response techniques in floating marshes resulted in a recommendation to not cut live vegetation (Henry et al. 2003); and
- The raking and cutting of heavily oiled vegetation mats (rooted but dead vegetation) in *Spartina alterniflora* salt marshes during the *Deepwater Horizon* spill, to expose and remove underlying thick emulsified oil layers had generally positive results compared to no treatment (Zengel and Michel 2013; Zengel et al. 2015; see case history in Chapter 4).

The strongest justification for cutting is made for the protection of wildlife. However, there is usually no careful discussion as to whether a given oiled marsh poses a clear and present danger to wildlife, and for how long. Often oiled marshes are less of a threat by the time discussions of cutting take place; thus, the perceived tradeoff of wildlife protection for marsh injury is unfairly weighted toward the former. Prior to the decision to cut oiled marsh vegetation, responders should involve experts in both marshes and the wildlife at risk to make a balanced evaluation of the tradeoffs, including the exposure pathways from an oiled marsh to wildlife, the reduction of that exposure/risk over time, and methods of determining this risk in the field.

Table 3-2 is a summary of the studies on the effects of cutting of oiled marshes, updated from Zengel and Michel (1996) where they made a qualitative judgment on whether the effects were positive, showed no differences, or were negative, based on the measured parameters and endpoints used in each study. One way to look at the results for all the cases in Table 3-2 is to consider the reasons for cutting and the potential consequences. If cutting is proposed to reduce the risk of continued oiling to wildlife or for aesthetic reasons, it is possible that 34% of the time, negative impacts to the vegetation could occur. If cutting is proposed to speed the recovery of the oiled vegetation, cutting is likely to be damaging or unnecessary for 66% of the time (sum of negative and no difference cases). Based on the 19 cases with data on direct comparisons, there is even a less likelihood that cutting will result in a positive effect on the vegetation and cutting will do more harm or have no effect on vegetation recovery for 79% of the time. Because of these kinds of study results, cutting has not been used very often in recent years.

Table 3-2. Summary of the relative effects of oiled marsh cutting for all studies and those studies with direct comparisons with cut and uncut vegetation (updated from Zengel and Michel 1996).

Effect of Cutting	All Studies (# of cases)	All Studies (% of all cases)	Cut vs. Uncut Comparisons (# of cases)	Cut vs. Uncut Comparisons (% of cases)
Positive (+)	10	34	4	21
No Difference (=)	8	28	8	42
Negative (-)	11	38	7	37
Total	29	100	19	100

Some key observations on cutting of oiled marsh vegetation updated from Zengel and Michel (1996) include:

- The studies of marsh cutting that resulted in positive effects almost always included a heavy fuel oil or heavy crude oil. This would also apply to the *Deepwater Horizon* spill where the oil on the marsh platform was a thick emulsified mousse that had properties similar to heavy oils.
- Most of the studies with positive effects were cases where the marsh was cut in fall or winter, when the plants are dormant and less likely to be stressed by both oil and vegetation removal. This effect was demonstrated by the experiments by Kiesling et al. (1988) where oiled vegetation cut in spring had lower recovery than those cut in winter.
- Cut vegetation that was submerged for a long period of time did not recover well, likely because the water layer would prevent oxygen transfer from air to the roots, which is essential for plant survival in water-logged, low-oxygen soils.
- Vegetation under salinity stress, such as water salinity that is higher or lower than normal, is more likely to have poor recovery after oiling and cutting.
- Physical damage from foot and vehicular traffic during cutting can cause additional damage to both the vegetation and the soils. Cleanup crews must follow specific guidelines to minimize foot traffic during cutting, such as working only from boats, standing on firm (unoiled) substrates, or 100% use of walking boards.
- There is not enough information to state if there are any differences in recovery of cut vegetation among herbaceous (grassy) species.

Flooding and Low-Pressure Ambient-Temperature Flushing

Table 3-1 gives flooding and low-pressure, ambient-temperature flushing a grade of “B” for all oil types. The objective of these techniques is to flush floating oil that is trapped in the fringing marsh vegetation to open water for collection. Water pressure should not exceed 50 pounds per square inch (psi) to minimize sediment erosion. These techniques sound like they would be beneficial, mimicking the action of natural currents. In practice, however, pushing a liquid (oil) on a liquid surface (water) is hard, particularly because the water surface is flat. Large volumes of water are needed to be effective, requiring a lot of equipment and materials in terms of pumps, hoses, working platforms, recovery devices, etc. A nearby water source of the same salinity as in the treatment area is also necessary. One of the biggest challenges is to get "behind" the oil that is trapped in the vegetation so it can be flushed to open water where the oil can be contained with boom and recovered using vacuums, skimmers, or sorbents. Flushing operations must consider tidal currents (flush on a falling tide) and wind (an onshore wind will push any released oil back onto the shoreline). Figure 3-10 shows the flushing operations at the Chalk Point spill site, demonstrating the complexity of the operations when the oil is in the marsh interior.

Figure 3-10. Intensive flushing operations along one of the trenches excavated at the Chalk Point, Maryland spill in April 2000. Flushing of oil from the marsh interior is very difficult. Photo credit: Jacqueline Michel.

Flushing can also be used to remove fluid oil stranded on the marsh surface. Figure 3-11 shows a barge-mounted flushing system developed during the *Deepwater Horizon* oil spill that was used to flush oil stranded on the marsh fringe in Louisiana (Zengel and Michel 2013). This approach allowed flushing to be directed from the landward side of the oiled band without placing equipment and crews on the marsh. The stranded oil was then flushed into the water where it could be collected. It worked well shortly after oil had stranded, if the oil was liquid; however, the oil quickly became too viscous to be mobilized by flushing. In addition, laid-over heavily oiled vegetation mats in some locations baffled the flushing spray, which also limited effectiveness. Even raking the vegetation mats first and then flushing was not effective on thick emulsified oil. The flushing pressure required to mobilize the emulsified oil for collection would have resulted in surface erosion of the marsh.

Figure 3-11. The barge-mounted flushing system that had a long-reach mechanical boom with a spray bar attached, *Deepwater Horizon* oil spill. The angle and pressure of the water spray had to be adjusted to minimize sediment erosion. This technique was not effective in some areas because the emulsified oil was too viscous to be flushed. Photo credit: Scott Zengel.

Shoreline Cleaning Agents

Shoreline cleaning agents (also called surface washing agents) are products that contain surfactants, solvents, and/or other additives that work to remove oil from solid surfaces, such as seawalls and marsh vegetation, but does not involve dispersing or solubilizing the oil into the water column. They are sprayed on the oiled vegetation, allowed to soak for a short period, then the oil is removed by flushing, taking care to recover the released oil, most often using sorbents. Many products promoted as shoreline cleaning agents are essentially industrial cleaners that emulsify the oil, much in the same way that dishwashing soap cleans the grease off dishes. The treated oil is broken into small droplets that are kept in suspension by the surfactant. These products are called “lift and disperse” types, and they should not be used in any manner during an oil spill where they or the treated oil will be released to the environment. However, there are products that meet the “lift and float” description, where the product increases the effectiveness of flushing to remove and recover the oil[3]. As indicated in Table 3-1, they would be considered for use for medium and heavy oils that thickly adhere to the vegetation.

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[3] Surface washing agents are discussed in the 2009 Selection Guide, available at: https://www.nrt.org/sites/73/files/Selection%20Guide%20for%20Oil%20Spill%20Response%20Countermeasures%20(Paper%20Version).pdf

Pezeshki et al. (1995, 1997, 1998, 2001) conducted a series of laboratory and field experiments where they applied crude oils and Bunker C fuel oil to oiled salt and freshwater marsh plants in Louisiana, then applied the surface cleaning agent Corexit 9580 on some of the plants 1-2 days after oiling to compare impacts and recovery with oil alone. Note that they mostly applied the oil to the vegetation. They found that using Corexit 9580 on plants oiled with the crude oils had some short-term benefits of increasing gas exchange of the vegetation and decreasing leaf death, but the long-term outcome was similar regardless of treatment. They concluded that use of a shoreline cleaning agent with crude oil spills did not have any long-term positive or negative impacts on the recovery of oiled marshes. However, use of Corexit 9580 increased plant survival compared to oil alone for the Bunker C treatments.

Bizzell et al. (1999) conducted a similar field experiment in Texas using weathered Arabian medium crude oil and a high and low dose of Corexit 9580 24 hours after oil application. They found that use of the cleaner did not affect microbial populations or the removal of oil from the top 5 cm of marsh soils. They did not report on the efficacy of Corexit 9580 application on oil removal from the vegetation.

One key point in these studies is that the shoreline cleaning agent was applied 1-2 days after oiling, which is not likely to occur during a real spill because of the time it would take to decide to use them, then get approval for their use. During the *Deepwater Horizon* spill, two different surface washing agents tested on oiled salt marsh were not effective in October 2010, due to the degree of oil weathering and emulsification, but also due to the thickness of the oil on the marsh substrate (Zengel and Michel 2013). Even raking followed by surface washing agent application and low pressure flushing only mobilized the immediate surface layer of the oil for collection, leaving much of the thick oil (>1 cm) remaining on the marsh. Teas et al. (1993) found that use of shoreline cleaning agents helped with mangrove survival if applied within seven days, but not after longer periods.

Responders have considered using shoreline cleaning agents on oiled marshes to reduce the contact hazard to wildlife using the marsh. Michel et al. (1998) tested the use of Corexit 9580 on salt-marsh vegetation in Maine during the *Julie N* spill, nine days after oiling by an IFO 380 (a moderate-heavy fuel oil) in late September (Figure 3-12). The agent removed about 50% of the oil on one side of the leaves; in comparison, ambient temperature water flushing removed no oil. Full-scale use was not recommended because very little oil was recovered; instead, a large amount of the released oil became suspended in the water and was not contained by boom or sorbents. Also, the logistics to apply the product to the wide band of oiled marsh in an area with a 3 m tidal range proved very difficult. One possible application might be to clean fringing vegetation along rivers and lakes, where the water level changes are relatively small. The marsh fringe is an important edge and transition zone that is heavily used by fish, invertebrates, and birds; thus, speeding the removal of oil as a contact hazard could have ecological benefits other than vegetation survival. However, so far, surface washing agents in oiled marshes have only been used on a small scale, often during field tests, with limited effectiveness and considerable logistical requirements and environmental concerns. Use of surface washing agents in oiled marshes may not be feasible as a large-scale solution at present.

Figure 3-12. Test of surface washing agent (Corexit 9580) during the September 1996 *Julie N* spill in Portland, Maine. (left) After application and flushing. Compare the degree of oiling on the vegetation in the treated area versus the marsh in the upper left corner. (right) Close up of the treated vegetation. About half of the oil on one side of the vegetation was removed. Photo credits: Jacqueline Michel.

Enhancing Bioremediation (Nutrient Enrichment and Soil Oxidants)

Nutrient enrichment is a type of bioremediation that involves the addition of nutrients (generally nitrogen and phosphorus) to the marsh to accelerate the degradation of oil hydrocarbons by natural microbial processes. It is one of the least intrusive treatment options available for marshes. There are many types of fertilizers that can be utilized to supply the soil with the needed phosphate, nitrogen, and any other limiting nutrients; however, they can be categorized as one of three types: water-soluble inorganic nutrients, slow-release fertilizers, and oleophilic fertilizers. Nutrients can be applied by hand to specific areas or by aerial spraying of granules from a helicopter (as was done for the Chalk Point, Maryland spill in 2000).

In 2004 the U.S. Environmental Protection Agency published a comprehensive summary of bioremediation options for oil spills in salt marshes and relevant literature, and provided guidelines for design and planning of bioremediation treatments in salt marshes (Zhu et al. 2004). They published a similar work that included freshwater wetlands (Zhu et al. 2001). Both reports provide objective, scientific reviews of all the field and laboratory studies done at that time, and there has been little additional research of bioremediation since then that changes any of their conclusions. Recent reviews of bioremediation of coastal environments (Nikolopoulou and Kalogerakis 2009; Mercer and Trevors 2011) have come to the same conclusions. The key point about nutrient enrichment in marshes is this statement in Zhu et al. (2001):

> "*all the nutrients in the world would not stimulate biodegradation if oxygen were the primary limiting material*."

There are few feasible techniques to increase the availability of oxygen in fine-grained, organic-rich marsh soils; those techniques used on land, such as tilling, forced aeration, and the addition of chemical oxidants, are too damaging to marsh soils. The only "successful" treatments using nutrients to speed the microbial degradation of oil in marshes were where the oil was on the marsh surface, not penetrated into the soils. In these studies, the addition of nutrients did speed the rate of loss of the alkane fractions (the most readily degraded components in oil) but, at the end of the study (usually several months) the differences in degradation between treatments with and without addition of nutrients were small. Field studies and most laboratory studies were unable to demonstrate any increase in the rate of loss for the aromatic fractions, those that contribute most to the chemical toxicity of oil.

One exception was the series of greenhouse experiments by Mendelssohn and Lin (2002), where they were able to increase the rate of loss of the aromatic fractions with application of fertilizer, a soil oxidant (that converts slowly to hydrogen peroxide, providing a source of oxygen), and KH_2PO_4 to buffer the high pH that might be caused by the soil oxidant, but only in sods where the water table was kept at 10 cm below the marsh surface. Although the rate of loss of the aromatic fractions increased, the researchers ultimately concluded that the losses were likely due to the addition of the KH_2PO_4 rather than the soil oxidant. In another set of experiments, Mendelssohn and Lin (2002) compared application of fertilizer, microbial seeding, and soil oxidants on vegetation sods with mineral and sandy sediments. They found increased oil degradation, including the aromatics, four months after application of fertilizer, but not the microbial seeding or soil oxidant.

Zhu et al. (2004) conclude by saying that on some coastal wetlands, nutrients might still be a limiting factor and nutrient addition could speed oil degradation if the oil does not penetrate deeply into the anoxic zone of the marsh soils. They also point out that nutrient addition could stimulate plant growth, which could accelerate the overall recovery of the habitat. Several studies have been done to test this assumption, with conflicting results (Lin and Mendelssohn 1998; Lee et al. 2001; Mendelssohn and Lin 2002; Tate et al. 2012). Therefore, adding fertilizers may or may not have an effect on vegetation growth, depending on site conditions.

These conclusions mostly apply to freshwater marshes as well (Zhu et al. 2001). The main differences are that freshwater environments do not have the daily tidal flushing regime that can quickly wash out applied nutrients, so the amendments can last longer; and some freshwater wetlands can be nutrient limited, particularly highly organic peat and tundra environments.

Sometimes, an argument is made that adding nutrients, just in case they might be helpful, at least does not do any harm. However, over-enrichment and eutrophication concerns may also need to be considered during nutrient addition in some settings. Any addition of nutrients to an oiled marsh needs to be based on site-specific considerations and best available science.

Marsh Responses to In Situ Burning

A review of the literature and spill histories provided by responders identified 31 oil spills, three field experiments, and three laboratory studies where in situ burning (ISB) was conducted in marshes. Appendix D summarizes these cases in chronological order. Of the 31 oil spills, 27 were light to medium crude oils and 4 were light refined products.

<u>Vegetation Recovery after In Situ Burning</u>: For those 24 spills (including two field experiments) listed in Appendix D where the vegetative recovery was documented from field studies or estimated based on the degree of recovery as of the last field survey, the vegetation is estimated to have recovered within:

- <1.5 years for eleven spills (46%);
- 1.5 to 5 years for eight spills (33%);
- 5 to 10 years for two spills (8%); and
- Greater than 10 years for three spills (12%).

Of those three spills with greater than 10 years of recovery, two were in muskeg and peat soils, and one was the Chiltipin Creek site in Texas where other factors (drought, feral hog, and seismic survey damage) likely extended the recovery beyond 10 years. The two spills with vegetative recovery estimated to have occurred within 5-10 years were the Meire Grove site that had extensive physical damage resulting from other cleanup activities pre- and post-burning and the Lafitte Oil Field Site 3, where a site visit in year eight found the vegetation mostly recovered but lower in species richness and with some elevated TPH in the soils.

Based on these results, when an ISB is used as an oil spill countermeasure in a wetland, if done following appropriate guidelines, the vegetation is likely to recover within five years, and more likely within 1-2 growing seasons.

Figures 3-13 and 3-14 shows time-series photographs two marsh burns in Louisiana. Baustian et al. (2010) studied the recovery of the Chevron Empire marshes: plant biomass and species composition returned to control levels within nine months; although species richness remained somewhat lower. Aboveground and belowground plant productivity recovered within one growing season. They concluded that burning was very effective in allowing ecosystem recovery for oiled marshes.

Figure 3-13. Mosquito Bay, Louisiana in situ burning of a condensate spill in a brackish water marsh. (left) April 2001 right after the burn. The arrow points to the fire break created by laying down the vegetation with airboats. Note that the fire mostly burned to the downwind water edge. (right) Same area in March 2003, showing good recovery of the vegetation. Photo credit: Louisiana Oil Spill Coordinators Office.

<u>Oil Behavior and Weathering in Soils after In Situ Burning</u>: Most studies have documented that burning results in removal of most of the oil on the marsh surface, and residual concentrations generally decreased over time. Even at the Chiltipin Creek, Texas site, where TPH concentrations in the soil remained elevated in small areas for three years, by year five, the PAH concentrations in these small areas decreased to very low levels (Hyde et al. 1999).

Figure 3-14. Chevron facility near Empire, Louisiana where in situ burning was conducted in a brackish water marsh. (left) October 2005 right after the burn. The arrow points to the fire break created by laying down the vegetation with airboats. Photo credit: Amy Merten. (right) March 2006, five months after the burn, showing good recovery of the vegetation. Photo credit: Gary Shigenaka.

Penetration of oil into marsh soils is of particular concern because of the slow rate of weathering in fine-grained, organic soils with low oxygen and flushing rates. Both field and laboratory burns have shown that burning does not remove any of the oil that has penetrated into the marsh soils. The Mosquito Bay, Louisiana spill of condensate was not burned until days 7 and 8 after the release, thus oil penetrated into the numerous fiddler crab burrows. After the burn, the condensate was readily visible in most burrows (Figure 3-15, right); in fact, the oil would pool on the surface in footprints created by observers, then burst into flame because the soils were still hot enough to cause ignition of the vapors when exposed to air on the surface. Oil remaining in burrows was also noted at the Chevron Empire spill in Louisiana after Hurricanes Katrina and Rita (Figure 3-15, left), when the oil stranded on the high marsh surface for weeks before it was burned (Merten et al. 2008).

Pipeline releases can result in oil that is trapped in the soils around the release site, particularly in floating (flotant) and quaking (tremblant) marshes, where the oil can be trapped below the marsh and will not burn. Under these conditions, vegetation recovery is slower due to the high degree of sediment contamination, leaving a denuded area in the immediate vicinity of the release site, as shown in Figure 3-16.

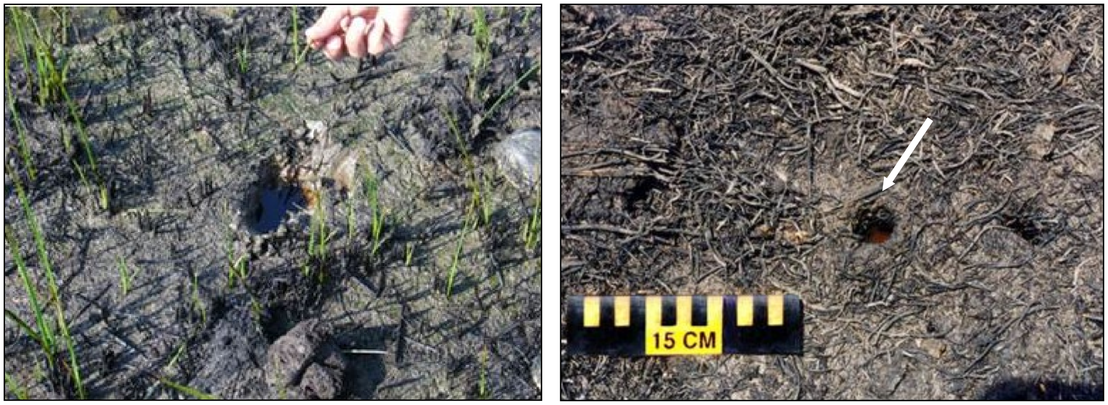

Figure 3-15. In Situ burning will not remove oil that has penetrated into the marsh soils. (left) Chevron Empire burn; (right) Mosquito Bay, Louisiana burn. Arrow points to the unburned, liquid oil in the burrow. Photo credits: Jacqueline Michel.

Figure 3-16. (left) XTO pipeline spill on 22 June 2018, seven months after the release, showing vegetation recovery except around the release site, indicated by the wooden poles. Photo credit: Brandi Todd, NOAA. (right) Delta Farms flowline spill in quaking intermediate marsh in early December 2017, with good vegetation recovery three years later (and one year after a second burn), except at the immediate release site, with the unvegetated area decreasing in size each year. Photo credit: Scott Zengel.

Williams et al. (2003) also noted that the diesel penetrated into the soils at a spill north of the Great Salt Lake, Utah and was not removed in the burn conducted six weeks after the release. The PAH concentrations actually increased after the burn, which they suggested was due to wicking of the oil in the soils by the heat of the burn. Eventually, the areas of persistently elevated PAHs in the soils were tilled and fertilized.

One common feature of examples where oil penetrated the marsh soils and was not removed during the burn, is that the oil remained in the marsh for at least one week prior to the burn. Rapid removal of oil by burning would help reduce the potential for deep penetration and less efficient removal during a burn.

The very long recovery for the ISB in highly organic soils (peat, fen, muskeg) is directly related to the deep penetration of oil into these soils when the water table is below the surface. The heat of the fire reduces the viscosity of the oil, and it readily penetrates the loose organic soils. The Kolva River burn was conducted without any approvals and resulted in oil penetration of over 1 m (Hartley 1996).

Blenkinsopp et al. (1996) found oil penetration to 40 cm in the bogs in northern Canada; the oil was only lightly weathered even after 24 years. They also noted that thick waxy crusts (burn residues), though highly weathered, formed physical barriers to plant regrowth. For other ISBs in marshes, the oil mostly stayed on the surface and was removed by natural weathering processes within a year or so (see Appendix D). Where there were heavy burn residues on the surface, in most cases, the residues were manually removed (Chiltipin Creek, TX; Tunnell et al. 1995) or raked to break up the residues (Michel and Zengel 2021). These efforts to remove or break up heavy surface burn residues were determined to speed vegetative recovery.

Mendelssohn et al. (2001) included in one of their laboratory experiments a study to determine if ISB affected the removal rate of oil penetrated into marsh soils. They added a small amount of either diesel or crude oil to the surface of the potted plants 24 hours prior to ignition in the burn tank—not enough to affect the vegetation, but enough to be able to track any reductions due to the burn. They found that burning with +10 cm, 0 cm, and -2 cm of water relative to the substrate did not reduce the amount of the crude oil in the soils but reduced the amount of added diesel by a factor of 10. It is likely that elevated temperatures more readily mobilized the low-viscosity and less sticky diesel.

In summary, ISB in marshes and organic soils results in rapid removal of surface oil, but it will not remove oil that has penetrated into the soils or is trapped below the marsh surface, such as in floating marshes. Under ideal conditions, there will be little subsurface oil; however, burns in peat soils can result in deeper penetration of oil into the subsurface. It is important to remove the burn residues shortly after the burn (using flushing, manual removal, or use of sorbents) because it has been shown that these residues weather slowly and can delay habitat recovery.

<u>Faunal Recovery after In Situ Burning:</u> There are very limited data on the impacts to marsh-associated fauna during an ISB and the relative rate of recovery after the burn. If studied at all, data are available for

at most one year post burn. For the March 1993 burn of aviation fuel in a snow/ice covered pond at the Naval Air Station Brunswick, Maine, studies of fish, birds, mammals, and benthic communities showed normal species abundance and composition by summer (Metzger 1995). At the Meire Grove spill in Minnesota, with light refined products that were burned in a small pond in September 1992, initial impacts to benthic invertebrates were severe. However, after one year Zischke (1993) noted that there was considerable recovery, with higher numbers of invertebrates from the oiled/burned pond and higher midge species richness, compared to a control pond. For a small burn area in Texas in October, Holt et al. (1978) documented impacts to invertebrates for the first month after a crude oil burn, with recovery within six months. McCauley and Harrel (1981) reported reduced invertebrate abundances in both oiled/burned and clean/burned study plots versus other treatments and controls in a brackish marsh along the Neches River in Texas six months after a January burn of crude oil. It should be noted that vegetative recovery for the Neches River burn was poor as well, due to high levels of freshwater due to floods. Michel et al. (2002) reported seeing large numbers of fiddler crabs six months after the Mosquito Bay, Louisiana ISB. Martin (2010, pers. comm.) reported seeing fresh crayfish burrows the day after the burn at Refugio, Texas. Mendelssohn et al. (1995) reviewed the limited prescribed burning literature on impacts of marsh burning (without oil) on fauna and found few studies. There were no significant effects on fauna as a result of marsh burning in these studies.

With such limited data, it is hard to make anything but general statements, such as, animals at the surface are likely to be killed if they are not able to escape into burrows or move out of the burn area. There is evidence that burrowers can survive the temperature effects of burning. Recovery is likely better if there are no burn residues or the residues are removed.

Guidelines for Considering In Situ Burning of Oil Spilled in Marshes

Oil spilled in marshes poses many difficult tradeoffs in terms of the potential impacts of the oil versus different response options. For ISB, the evaluation of the tradeoffs usually has to be conducted quickly, before the oil spreads, penetrates into the soils, weathers, or changes in some way that makes ISB less effective. Also, burning is often appropriate for small spills in the marsh interior where access for manual removal can cause extensive habitat damage and slow recovery. In this section, guidelines for considering when to use ISB in a marsh are discussed, with as much scientific data to support them as possible.

<u>Time of year</u>: Though it is not possible to pick the time of year for a spill to occur, responders need to consider the time of year in determining how quickly vegetation may recover from a burn. Mendelssohn et al. (1995) assessed studies of prescribed burning (for habitat management) where burning resulted in an increase, decrease, or no change in plant growth compared to appropriate controls, by season. They

reviewed 34 studies where recovery times were less than 1.5 years and 20 studies where recovery times were greater than 1.5 years. Burns in summer had the highest percentage of events that resulted in a decrease in vegetative growth. For burns with recovery times less than 1.5 years, 55% of the burns in summer resulted in a decrease in vegetative growth compared to 20% in fall, 33% in winter, and 11% in spring. For burns with recovery times greater than 1.5 years, the percentage of burns that resulted in a decrease in vegetative growth were 42% in summer, 25% in fall, 0% in winter, and 0% in spring. These studies showed that, regardless of season, for 68-80% of the time, prescribed burning resulted in vegetative growth that was equal to or greater than controls.

> *The rule of thumb, based on both understanding of the life history of plants and prescribed burning studies, is that vegetation recovery is likely to be slowest if burned during the summer and fastest if burned in the winter and early spring.*

Plant Species: Species vary in their tolerance to fire as seen in the prescribed burning and fire ecology literature (e.g., Nyman and Chabreck 1995; Zengel et al. 2003), and thus in their likely response to ISB as a treatment option. Dahlin et al. (1999) and Zengel et al. (2003) provided a detailed summary of what is known from the fire ecology literature and an evaluation of the potential for using ISB for the following plant communities: trees, shrubs, grasses, desert habitats, and wetland grasses and sedges (including over 200 dominant species across U.S. ecoregions). Nearly all wetland grasses and sedges were considered to have high or very high potential for a successful ISB.

Lin et al. (2005) noted that recovery after their ISB laboratory experiments was species-specific when there was not a water layer over the marsh soils during the burns. *Sagittaria lancifolia* and *Spartina alterniflora* are species that have large and/or shallow rhizomes that were affected more by burning, whereas *Spartina patens* and *Distichlis spicata* are species that can have very dense stems (up to 5,000/m^2) and rhizomes occurring at deeper depths where thermal stress from burning is reduced. They also found that *Spartina patens* and *Distichlis spicata* quickly generated new shoots from surviving rhizomes, thus were able to outcompete other species in the first several months. However, over time, the other species were able to catch up and the vegetation returned to its normal species composition. They concluded that surviving rhizomes of *Spartina patens* and *Distichlis spicata* could rapidly recover after burning. This rapid regrowth of vegetation is important because the aboveground vegetation provides a pathway for oxygen transfer from air to the roots, which is essential for plant survival in waterlogged, low-oxygen soils.

However, species responses to oiling and burning can vary, depending on other factors. Lindau et al. (2003) found rapid recovery of stem height and density and carbon fixation after a field ISB experiment for both *Spartina alterniflora* and *Sagittaria lancifolia* after one year, with aboveground biomass higher than controls. They suggested that these species might be utilizing oil and dead vegetation from the burn as sources of nutrients. Zengel et al. (2018) reported slower recovery than expected for *Phragmites australis* after an oiled marsh burn of emulsified crude oil in the interior of a tidal freshwater marsh on the Mississippi River delta, postulating that the intense summer burn and stress from high water levels and/or non-native *Phragmites* scale insect damage may have contributed to slower *Phragmites* recovery; however, rapid establishment of abundant native vegetation to the site, especially *Sagittaria* spp., was seen as a positive outcome by wildlife managers.

<u>Marsh Soil Type</u>: The biggest concern with the use of ISB in marshes is for highly organic soils where the peat soil itself could ignite, causing lowering of the marsh elevation, damaging roots and the seed bank, etc. Oil degradation rates for subsurface oil in acidic, anaerobic soils are slow and can take many decades (more than 24 years as reported by Blenkinsopp et al. 1996). The amount of litter on the marsh surface at the time of the burn can also influence the recovery and composition of the vegetative community. Pahl et al. (1997) suggested that the ISB at the Rockefeller Refuge in Louisiana removed the litter, which favored the rapid growth of *Bolboschoenus* (*Scirpus*) *robustus* over the pre-burn dominance of *Distichlis spicata* and *Spartina alterniflora*. There are similar examples from the prescribed burning literature. There are many cases where marsh burning, both with and without oil, results in temporary shifts in dominance to bulrush species (*Schoenoplectus*, *Bolboschoenus*, or *Scirpus* spp.). This is not necessarily an undesirable outcome, as prescribed marsh burning has often been conducted to favor bulrush species for wildlife management purposes.

<u>Water Levels during a Burn</u>: Soil temperatures of 60-65°C are lethal to plants. Therefore, whether conducting a prescribed burn or responding to an oil spill, it is always recommended (but not required) that standing water should cover the marsh surface during the burn, to protect plant rhizomes from thermal stress and prevent ignition of organic soils. For oil spills, an additional benefit of a water layer is prevention of oil penetration into the marsh soils. The marsh sites, and the locations within some marshes, with some of the longest recovery periods include those that had little to no water present during the burn, such as Chiltipin Creek, Texas which was predicted to take 14-15 years to fully recover to its climax species distribution (Hyde et al. 1999).

Lin et al. (2002a, 2005) conducted a series of burn-tank experiments that replicated in situ burn temperatures, with thermocouples inserted into the marsh soil of potted plants at different depths to help answer the question of how much water was enough to protect the plants during ISB. Their first study (Lin et al. 2002a) showed:

- A water layer of 10 cm was ample to protect the marsh soil from burning impacts, with soil temperature below 37°C and plant survival and regrowth high;
- A water table 10 cm below the marsh surface resulted in soil temperatures of 120°C at 2 cm soil depth and almost no post-burn recovery of *Spartina alterniflora*; and
- At water levels of 0 and 2 cm over the marsh surface, the soil temperatures were low enough for the plants to survive, but they died from exposure to the diesel oil used in the experiment.

With these results, Lin et al. (2005) conducted another set of experiments to separate the oil stress from the thermal stress at water levels less than 10 cm over the soil surface. They also wanted to determine if the effect of ISB differs with the marsh type and oil type burned. This second study showed:

- Water layers of 2 and 10 cm overlying the soil surface were sufficient to protect marsh vegetation of all three types of marshes from burning impacts. Soil surface temperatures did not exceed 40°C with 10 cm and 50°C with 2 cm of water overlying the soil surface;
- A water table 2 cm below the soil surface resulted in soil temperatures of >100°C at 0 cm to <40°C at 5 cm below the soil surface and higher impacts to *Spartina alterniflora* (30% reduced survival) and *Sagittaria lancifolia* (50% reduction in survival) because these species have rhizomes close to the surface; and
- *Spartina patens* and *Distichlis spicata* were not affected by ISB with the water table 2 cm below the soil surface (dense stems and deeper rhizomes).

Experience during ISBs at actual spills also indicates that if the marsh soils are water saturated to the marsh surface, the plants will mostly survive. More water is better, but not essential. However, burning of oil on dry marsh soils should be carefully considered in terms of the tradeoffs associated with different response options and resources at risk.

<u>Flooding Post-burn</u>: Studies of prescribed burns have shown that certain species are more likely to die if they are completely submerged under water for several weeks after the burn. *Distichlis spicata, Panicum hemitomon,* and *Typha* spp. are particularly sensitive to post-burn submergence (Dahlin et al. 1999). Prescribed burns are often scheduled in the fall, when water levels are low, so the plants are better prepared for spring flooding. McCauley and Harrel (1981) attributed the very poor recovery of *Spartina patens* after test burning of a spill in the Neches River, Texas to persistent flooding for months. Pahl et al. (2003) also noted slower recovery of *Distichlis spicata* when flooded after burning. Holt et al. (1978) reported the lowest recovery of a heavily oiled *Spartina alterniflora* occurred in an area of standing water.

<u>Oil Type</u>: Oil type and degree of weathering will influence the efficiency of the burn, the potential for burn residues, and the thickness and type of burn residues remaining on the marsh surface. Heavier oils and more weathered or emulsified oil generate more burn residue. Table 3-3 summarizes the likely behavior of burn residues from different oil types when burned on land. In addition, the burn residue from heavier oils can be heavier than water and sink, a behavior that is more likely for spills in freshwater habitats. Highly weathered or emulsified medium crude oils and intermediate products can behave more like heavy oils in some circumstances. Laboratory studies have shown strong correlation between the densities of the original oil and the resulting burn residue: crude oils with densities greater than 0.864 g/cm^3 (or API gravity less than 32) are likely to produce burn residues that sink in seawater (S.L. Ross Environmental Research Ltd. 2002).

Table 3-3. Behavior of burn residues by oil type for on-land burns (from Scholz et al. 2016).

Oil Type	Behavior of Burn Residue on Land
Gasoline products	• Will burn; will not leave a significant amount of residue.
Diesel-like products and light crude oils Diesel, No. 2 fuel oil, Light concentrate, West Texas crude oil	• Burn residue is mostly unburned oil that penetrated into the ground, root cavities, and burrows with small amount of soot particles that can be enriched in heavier PAHs. • Remains liquid; can be recovered with sorbents and flushing.
Medium crude oil and intermediate products South Louisiana crude oil, IFO 180, Lube oils	• Burn residue can be pockets of liquid oil, solid or semi-solid surface crusts or sheets, and heavy, sticky coating on sediments. • Liquid oil can be flushed. Semi-solid and solid residues can be manually removed. • Remaining residues can be tilled and fertilized in appropriate habitats.
Heavy crude oils and residual products Venezuela crude, San Joaquin crude, No. 6 fuel oil	• Difficult to burn, so often must add a lighter oil to start the burn. • Leaves heavy, sticky residue that is a mix of unburned oil and semi-solid burn residue, requiring extensive cleanup. • Remaining residues can be tilled and fertilized in appropriate habitats.

Another factor concerning oil type (other than safety issues) is the toxic effects of the oil on the marsh community prior to the burn. Lin et al. (2005) did not detect any differences in response of ISB of diesel versus crude oil in their burn tests. However, several spills have shown that light fuel oils and condensates caused plant mortality during the period that the oil was in the marsh prior to the burn, such as the Mosquito Bay and Sabine Point spills of condensate in Louisiana and the diesel spill in Corrine, Utah (Michel et al. 2002). Burning under these conditions will not avoid vegetation and faunal mortality from oil exposure prior to the burn. If the release includes produced water, which has very high salinities, burning will not prevent vegetation mortality from salinity stress, such as that observed at the Time Energy Site 2 spill.

Fire Control: For most ISBs in marshes, the fire is extinguished when it reaches unoiled vegetation, particularly during the growing season when the vegetation is live. At this point, the smoke goes from black with soot to white with water vapor. However, real "control" of a fire in a marsh during a spill emergency is difficult, and responders must be prepared for the fire spreading to unoiled areas. In three of the case histories in Appendix D, the burned area was much larger than the oiled area. For the Mosquito Bay spill, the burned area was eight times the oiled area (4.9 ha vs. 40 ha; Figure 3-13); for the Louisiana Point spill, the burn area ten times the oiled area (5.3 ha vs. 55 ha); and for the Delta Farms spill, the burn area was nearly seven times the oiled area (0.23 ha vs. 1.5 ha). The types of firebreaks possible in a marsh, such as laying down and wetting the vegetation using an airboat, are not sufficient to contain a hot fire. The burn can spread to unoiled areas at sites: 1) that have not been burned recently (thus have abundant natural fuel present); 2) where fire breaks cannot be completely cleared; 3) without a lot of free-standing water; and 4) with dry or dead vegetation. Burns that escape control can create significant human health and safety risks, property loss, and additional natural resource damages.

Presence of Protected Species: If there is potential for a burn to impact species that are listed under federal endangered species laws or that are otherwise protected (e.g., bald eagles, state protected species), a burn might not be appropriate, particularly if there is a risk that the burn could spread beyond the oiled area. Fast burns may not allow animals to escape the fire. The tradeoff analysis of risks from the oil versus risks from the burn should be discussed with the trustee agencies.

Selecting Appropriate Cleanup Endpoints for Marshes

The NOAA Shoreline Assessment Manual (NOAA 2013) includes a discussion of the process for establishing cleanup endpoints for different habitats. Cleanup endpoints appropriate for marshes are generally as follows:

- No free-floating oil in the marsh;
- No oil on vegetation that can rub off on contact;
- No oil greater than 0.5 cm thick on the marsh surface; and/or
- As low as reasonably practicable, considering the allowed treatment methods and net environmental benefit.

It is the last cleanup endpoint that requires the most discussion in terms of the tradeoff between the degree and duration of impacts from the oil versus the degree and duration of impacts associated with removal actions. From the discussion of cleanup methods in this chapter and the rates of recovery of oiled marshes in Chapter 2, clearly marshes most often recover on their own within one or two years for light to moderate oiling. In most cases, natural recovery is the best option. However, when marshes are heavily oiled, and particularly with thick oil on the marsh surface, removal actions are often needed to remove as much of the oil as feasible to speed the overall rate of recovery, without causing more harm than good.

Vegetation Planting as Part of the Response

Marshes that are severely affected by either oiling or response operations may be more susceptible to delayed or reduced vegetation recovery and habitat loss through erosion. In these cases, it may be necessary to conduct vegetation planting for shoreline stabilization or emergency restoration as part of the response. Figure 3-17 shows the benefits of planting to quickly re-establish vegetation at a site that was heavily oiled and intensively treated following the *Deepwater Horizon* oil spill (Zengel et al. 2015, 2021, 2022b). Planting resulted in much faster and more complete vegetation recovery in this case and reduced shoreline erosion rates (refer to the case history in Chapter 4). Planting also increases the rate of residual oil degradation in the soils through phytoremediation (Lin and Mendelssohn 1998).

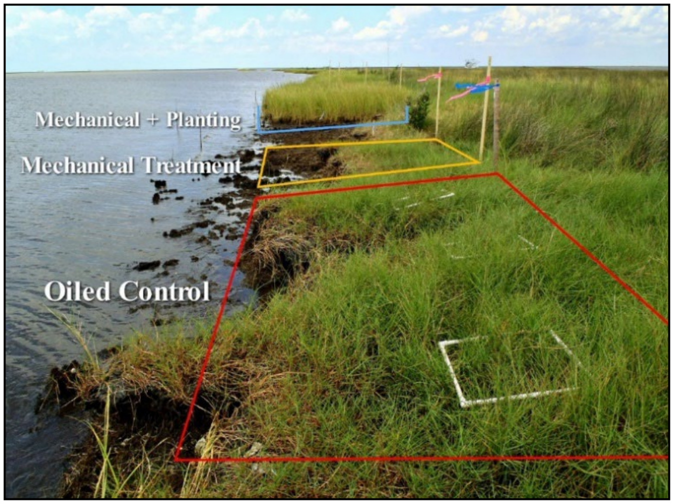

Figure 3-17. *Spartina alterniflora* was planted (bare root) along the heavily oiled and highly erosional salt marsh shoreline in Northern Barataria Bay, Louisiana immediately after mechancal treatment following the *Deepwater Horizon* oil spill. The mechanically treated and planted areas (background, blue outline) had good vegetative recovery as of September 2013 and less erosion, whereas the treated but unplanted areas (middle, orange outline) and oiled controls (natural recovery, not planted) (foreground, red outline) each had limited vegetation recovery and greater shoreline erosion. Vegetation in the non-planted areas was dominated by shorter *Paspalum vaginatum* rather than *Spartina alterniflora* which naturally dominates salt marsh shorelines in the region. Photo credit: Scott Zengel (from Zengel et al. 2021).

When oil removal requires intrusive methods that damage the marsh vegetation or soils, it may be necessary to conduct planting to stabilize or restore the site. Removal of oil from the marsh interior during the Chalk Point oil spill in Maryland (No. 6 and No. 2 fuel oils) required extensive trenching (Figure 3-4). Once the response operations were terminated, the Responsible Party conducted a marsh restoration project that involved filling in of the trenches with clean soil and planting marsh vegetation. Figure 3-18 shows the photographs of one of the heavily disturbed but restored areas only one year after vegetation planting. According to Gundlach et al. (2003), vegetative recovery was 70-80% after one year, and nearly 100% after two years. See also the case history in Chapter 4.

After the Exxon Bayway No. 2 fuel oil spill in the Arthur Kill in New York, some of the areas where the vegetation died and did not re-establish were planted three years later. Bergen et al. (2000) monitored vegetative recovery at marshes along denuded/planted marshes, denuded/not planted marshes, and unoiled marshes over the period 1994-1997 and found that the planted areas recovered well, despite the presence of residual oiling.

Positive results from vegetation planting in heavily oiled marshes after intensive treatments were also observed following the *Lang Fonn* No. 6 fuel oil spill in 1978 in the Potomac River Estuary in Maryland (Krebs and Tanner 1981), and after the *Amoco Cadiz* crude oil spill in France (Seneca and Broome 1982; Baca et al. 1987, see also the case history in Chapter 4).

Figure 3-18. Restoration including vegetation planting after trenching and flushing (see Figure 3-4) at the Chalk Point spill site. (left) July 2000; (right) July 2001, one year later. Photo credit: Jacqueline Michel.

Based on these results, replanting of marsh areas with heavy oiling, intensive treatment, high vegetation mortality, and/or high erosion risk should be a major priority during spill response.

It is recommended that vegetation planting be considered for cases with heavy marsh oiling that are likely to result in vegetation mortality, and as a possible condition for the use of intensive marsh cleanup methods because of the effectiveness of planting for limiting erosion, enhancing habitat recovery, and further improving oiling conditions (Zengel et al. 2015, 2021, 2022b). Planting is especially important where oil-impacted areas are left largely unvegetated, natural recovery may be delayed, background erosion rates are high, or wetland loss is a major concern. Vegetation planting following heavy oiling of marshes should be incorporated into shoreline treatment operations during emergency response for shoreline stabilization, for longer-term enhancement of oil removal, and for emergency restoration. Vegetation planting could also be considered for emergency restoration under the Natural Resources Damage Assessment (NRDA) process, to limit the degree and duration of impacts.

When planting is considered, the source of planting material and planting methods need to be carefully evaluated prior to implementation, including such factors as which native plant species and varieties are to be planted given the local habitat conditions, the oil tolerances of the selected species and varieties, wave exposure, planting of wild stocks versus cultivars (e.g., see Bernik et al. 2021), the use of local versus non-local plant sources, field transplants versus nursery grown material, bare root versus soil plugs or containerized plantings, planting density and spacing, site preparation, herbivory risk, and whether to use fertilizers or other soil amendments. Restoration guidance should be sought from both published sources and local and regional experts (i.e., restoration researchers and practitioners). Information on planting materials and methods from sources such as the USDA NRCS plant guides, as well as technical planting specifications from restoration programs and projects managed by local, state, and federal government agencies, can be very helpful with planning vegetation planting efforts following oil spills.

To address some of these questions, vegetation planting in oiled salt marsh mesocosms is currently being studied by NOAA NCCOS and OR&R in Charleston, South Carolina (Figure 3-19). The mesocosms were oiled with a heavy loading of marine diesel (3 L/m^2). The study is comparing post-spill planting with local wild transplants of *S. alterniflora* versus nursery-grown cultivars of the same species from Maryland. Bare root versus soil plugs (nursery plants) and soil cores (wild transplants) are also being examined. The original marsh vegetation died relatively quickly after exposure to fresh marine diesel. Plantings installed two months post-oiling also died, likely due to remaining oil sheens on the water which may have been remobilizing from the marsh surface during high tides. However, after a second round of plantings at eight months post-oiling, after oil sheens were diminished, the plants appeared to be surviving and growing steadily through two months of monitoring. Detailed results from this study should be available to spill responders in the next one to two years.

Figure 3-19. Oiled marsh vegetation planting study by NOAA in Charleston, SC. A) Experimental set-up, prior to oiling; B) Side-by-side vegetation comparisons post-oiling and shortly after planting, oiled control (dead, not planted) (left); unoiled control (healthy, reference) (middle); oiled, cut, and newly planted (right). Photo credit: Scott Zengel, Paul Pennington (NOAA).

Selecting Appropriate Response Options for Speeding Recovery of Oiled Marshes

Table 3-4 provides a matrix of likely marsh oiling conditions and potential response options, along with guidance on key issues and constraints based on the information summarized in Chapters 2 and 3. Again, it is important to note that often multiple response options will be used during a spill, for different oiling conditions or different phases of the response.

Table 3-4. Guidance on selecting appropriate response options for oiled marshes.

Oiling Condition	Response Options	Key Issues/Constraints
Free-floating oil on water in the marsh	In situ Burning	- Safety, fire control, sufficient water layer or saturated soils, oil type (mousse less likely to burn), amount of oil residue that will still need removal, time of year, species sensitivity, marsh soil type (peat soils are highly sensitive), flooding post-burn could cause plant mortality
	Vacuum	- Can remove large amounts of oil quickly before it becomes stranded, work from boats at water's edge will limit access to interior oil, ability to concentrate the oil to increase effectiveness, need to decant water to improve efficiency, avoid foot traffic on marsh surface
	Low-pressure Flushing	- Access, particularly ability to generate enough flow to push oil towards recovery devices, high oil viscosity will reduce effectiveness, potential to disturb soils

Oiling Condition	Response Options	Key Issues/Constraints
	Sorbents	- Loose sorbents (pads, snare) must be removed immediately, use walking boards or deploy from boats, can be slow and labor intensive
Thicker oil (>0.5 cm) on marsh surface	Natural Recovery	- Degree of exposure to physical removal processes, potential for exposure hazards for animals and long-term impacts to vegetation
	Manual Removal (rake, scrape)	- Access, use walking boards, risk of damage to live vegetation and disturbing soils, can speed of weathering of residues
	Vacuum	- Access, avoid foot traffic or use walking boards, potential to gouge the marsh soils and remove soils/vegetation, likely to leave thick patches, use low-pressure flushing to increase oil removal
	Low-pressure Flushing	- Access, particularly ability to generate enough flow to push oil towards recovery devices, high oil viscosity will reduce effectiveness, potential to erode soils
	In situ Burning	- Safety, fire control, saturated soils to prevent oil penetration into the soils, time of year may affect plant recovery, oil type (mousse unlikely to burn), amount of oil residue that will still need removal, species sensitivity, marsh soil type (peat soils are highly sensitive), potential to change soil elevation if organic soils burn, flooding post-burn could cause plant mortality
Thinner oil (<0.5 cm) on marsh surface	Natural Recovery	- More likely to weather to a thin, dry crust and be removed by natural processes
	Same Options as for Thicker Oil	- Consider risks of causing more damage during removal actions compared to rate of natural weathering
Heavy oil on vegetation	Natural Recovery	- Preferred tactic, unless there are key species of concern at risk
	Passive Sorbents	- Use only as long as oil is being released, closely monitor to make sure that the sorbents are properly deployed, remove prior to high water or waves to prevent stranding in the marsh
	Loose Organic Sorbents	- Consider how long before the oil weathers to a dry coat, application should be only a thin coating on the vegetation, will be difficult to apply to marsh interiors
	Vegetation Cutting	- Consider only if there are key species of concern at risk, consider how long before the oil weathers to a dry coat, may need to cut accessways to reach interior oil, use walking boards, test different tools to determine best tactic, consider possible delayed vegetation recovery and habitat loss
	Surface Washing Agents/Flushing	- Use when necessary to reduce contact hazard quickly, must wash to water (so only use when water levels cover the soils), use only products that lift and float, potential short-term increased aquatic toxicity, logistical constraints
Light to moderate oil on vegetation	Natural Recovery	- Preferred tactic particularly for light oils, small areas, dormant vegetation, some exposure to waves and/or currents
	Passive Sorbents	- Use only as long as oil is being released, closely monitor to make sure that the sorbents are properly deployed, remove prior to high water or waves to prevent stranding in the marsh

Oiling Condition	Response Options	Key Issues/Constraints
	Loose Organic Sorbents	- Consider how long before the oil weathers to a dry coat, application should be only a thin coat on the vegetation, will be difficult to apply to interior of the marsh

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CHAPTER 4. MARSH CASE STUDIES

Much of what we know about the impacts of oil and response options on marsh habitats has been learned through observations at spills. Case studies provide the basis for evaluating the tradeoffs of different response options, both during an emergency response and in planning for spills. Many of the studies of past spills have been cited in Chapters 2 and 3. In this chapter, four case studies are summarized, focusing on different types of oil and treatment methods used, and highlighting the lessons that were learned and have influenced future spill responses. The case studies are presented in chronological order.

Barge Florida, Buzzards Bay, Massachusetts, September 1969

Acute Toxicity and Long-term Impacts of No. 2 Fuel Oil
Up to 185,000 gallons of No. 2 fuel oil were spilled from the barge *Florida* into Buzzards Bay, Massachusetts in September 1969 resulting in heavy oiling of the Wild Harbor estuary. This spill has been well studied for nearly forty years because of its close proximity to the Woods Hole Oceanographic Institute. Salt marshes died within a few weeks, and in heavily oiled sediments, all benthic life was killed (Sanders et al. 1980). Two years later, soils with greater than 1-2 mg/g oil contained no living plants; vegetation regrowth occurred by rhizome spreading from the edge of live vegetation (Burns and Teal 1979). The heavily oiled marsh areas had fewer benthic species, and were dominated by opportunistic species such as the polychaete *Capitella capitata* that would bloom then crash, indicating poor recruitment for five years (Sanders et al. 1980). Krebs and Burns (1977) followed the impacts of the spill on fiddler crabs for seven years. Starting in 1971, they documented decreases in fiddler crab density, reduced juvenile settlement, heavy overwinter mortality, uptake of oil into tissues, and behavioral disorders including locomotor impairment and abnormal burrowing. They found correlations of these effects with the persistence of the alkyl naphthalenes (2-ringed PAHs) in the oil. Only when these compounds decreased in 1976-77 was there successful recruitment of juvenile crabs, which started the recovery of adult populations seven years after the spill.

Nearly 40 years later, Culbertson et al. (2007) documented that, in a small area that still contained relatively unweathered oil in the subsurface, fiddler crabs avoided burrowing into oiled layers, suffered delayed escape responses, had lowered feeding rates, and achieved 50% lower densities than in control areas. Studies 38 years after the spill showed that mussels transplanted into the oiled areas had slower growth rates, shorter mean shell lengths, lower condition indices, and decreased filtration rates, and salt marsh vegetation showed reduced stem density and above- and belowground biomass (Culbertson et al.

2008a,b). Peacock et al. (2005) showed that the oil persisted in a narrow band several meters wide and about 50 m long in the mid- to lower intertidal zone adjacent to one tidal channel, in the area where the oil initially was reported as being the heaviest. Thus, the areal extent of the persistent oil is small relative to the initial oiled area. They found that the highest oil concentrations (1-14.1 mg/g TPH) were between 4-20 cm below the surface, and they estimated that 100 kg of oil remained, representing 0.02% of the original spill volume.

Many factors combined to cause the acute toxic impacts and persistence of the subsurface oil from the *Florida* spill: Initial heavy loading (the oil was pushed by winds and tides into the impacted bay and persisted there for many days), a tidal range of nearly 2 m (so that the oil that stranded on the marsh at high tide was able to penetrate the sediments as the tides and groundwater levels in the marsh dropped), organic soils with slow weathering rates, a net depositional area (with sediment accumulation rates of 0.35 cm/year; White et al. 2005); and a sheltered setting.

Amoco Cadiz, Brittany, France, March 1978

Intrusive Treatment Delays Marsh Recovery

The T/V *Amoco Cadiz* spilled 70 million gallons of Arabian and Iranian light crude oil off the coast of Brittany, France in March 1978. The extensive marsh at Île Grande was heavily oiled, and the French military used vacuuming, high-pressure flushing, and excavation in attempts to clean the marsh (Figure 4-1). Following the spill, there were extensive areas with no vegetation cover. In many areas, only the aboveground marsh vegetation and oil had been removed; in other areas the entire marsh surface including the root mat had been removed to a depth of over 30 cm, and the creek banks were almost completely lacking vegetation, leading to extensive erosion.

Seneca and Broome (1982) conducted experimental and then larger-scale replanting activities to speed the rate of recovery. They eventually planted 9,700 transplants, half of them along the creek banks. Baca et al. (1987), in studies eight years later of the marshes that were intensively cleaned compared to oiled but not cleaned marshes and an unoiled marsh, found that the oiled but not cleaned marsh had recovered within five years by natural processes. In contrast, the oiled/cleaned/replanted marsh at Île Grande took 7-8 years to recover based on field transect data. The slower recovery was attributed to the destruction and compaction of roots, removal of the marsh substrate, and erosion of channels due to the lack of vegetation along the channel banks. They found that vegetation planting improved the rate of recovery because the vegetation stabilized open areas and provided attachment substrates for seeds and propagules, which sped the overall rate of revegetation (which was key to recovery of the marsh).

The rate of oil degradation in the marsh soils was a function of the initial degree of oil contamination, as studied by Mille et al. (1998) who collected soil samples seven times between 1978 and 1991. At the site with the lowest oiling (initially at 1,900 ppm TPH), the n-alkanes degraded within four years and all the oil was degraded after thirteen years. At sites with the highest oiling (33,000 and 230,000 ppm TPH), it took between 6-13 years for the n-alkanes to be degraded, and oil was still present thirteen years later.

Gilfillan et al. (1995) used historical aerial photography from 1971 and 1990 to assess the long-term recovery of marshes that were cleaned and not cleaned. They found that the oiled and cleaned marshes at Île Grande had between 23 and 39% less vegetated area, compared to an adjacent oiled and not cleaned marsh that had increased in area by 21%. They were able to map the distribution of marsh vegetation using aerial photographs and ground-control data into high marsh and low marsh. In 1971 prior to the spill, the cleaned marsh was composed primarily of high marsh; in 1990, the proportion of low marsh to high marsh increased significantly. In contrast, the composition of the marsh vegetation in the oiled and not cleaned marsh had not changed between 1971 and 1987. They attributed these changes in marsh coverage and type in the cleaned marsh to the removal of up to 50 cm of marsh soils during cleaning, which lowered the intertidal elevation of the marsh surface. Marsh vegetation is very sensitive to elevation and the frequency and duration of flooding. Because of the excessive sediment removal during cleaning, there was a shift in the vegetation to low- and mid-marsh species. Gilfillan et al. (1995) concluded that full recovery to pre-spill conditions had not occurred by 12 years post-spill. They predicted full recovery would require sediment accretion in the affected marshes.

This spill provided good scientific data that intrusive cleanup in a marsh will slow the overall rate of recovery, thus such treatment should be carefully evaluated. This greatly influenced future response strategies in spills around the world.

Figure 4-1. Heavily oiled marsh at Île Grande, France from the *Amoco Cadiz* oil spill. A) Aerial view of the heavily oiled marsh in March 1978. B) High-pressure flushing during cleanup by the French army in April 1978. C) Condition of the marsh in Fall 1978 showing extensive removal of the vegetation and the substrate. D) Condition of the marsh in 1986, eight years later showing late vegetation recovery. Photo credit: A. Miles Hayes; all others: Erich Gundlach.

Chalk Point, Patuxent River, Maryland, April 2000

Long-term Monitoring of Heavily Oiled Interior Marsh

On 7 April 2000, an estimated 140,000 gallons of a mixture of No. 6 and No. 2 fuel oils were released into Swanson Creek, the Patuxent River, and downstream tributaries from a pipeline rupture going into nearby Chalk Point Power Generating Station. The spill affected an estimated 76 acres of brackish marsh (dominated by *Spartina cynosuroides* and *Spartina alterniflora)*, with extensive areas of heavily oiled interior marsh habitat. There was intensive treatment including trenching, flushing, and use of sorbents in accessible marsh areas (see Figures 3-4 and 3-15); however, there was no treatment in other heavily oiled interior marsh areas that had limited access. Because of the predicted long-term persistence of oil-related impacts, NOAA funded a study of the oiled wetlands in 2007, seven years after the initial spill (Michel et al. 2009).

Overall, the oil in the highly organic marsh soils had undergone little to no additional weathering since Fall 2000, based on comparisons of PAH depletion ratios from samples collected in Fall 2000, Summer 2001, and Summer 2007. There were likely two factors limiting natural weathering processes in the marsh soils: slow physical removal processes and low oxygen availability. The interior marsh habitat is flooded by daily tides through many small channels. During spring high tides, there can be 20-30 cm of water in the marsh. The marsh surface has a lot of micro-topography with low areas between dense clumps of stems that hold pools of water during low tide. The soils in these low areas are very soft and water saturated. During spring low tides, the marsh soils do drain as low as 30 cm, as evidenced by the fact that the oil penetrated to these depths in some areas. Tidal flushing may have been a mechanism for removal of bulk oil stranded on the surface initially; however, it would not be effective at mobilizing oil from below the marsh surface. There are few bioturbating benthic biota in these marshes. Photo-oxidation does not occur below ground. Therefore, the only other removal mechanism would be microbial degradation, which obviously is very slow in these soils. With the slow weathering of the oil, nearly half of the 24 soil samples collected in 2007 showed evidence of toxicity in amphipod toxicity tests.

Visually, the marsh vegetation looked like it had recovered; however, the stem density and stem height of *Spartina alterniflora* (but not *Spartina cynosuroides*) were significantly lower in the oiled versus unoiled sites. In contrast, belowground biomass was significantly lower in the *Spartina cynosuroides* habitats but not the *Spartina alterniflora* habitats. The reasons for these differences may be related to the relative distribution of above- versus belowground biomass and the types of biomass for each species. *Spartina cynosuroides* has more and larger rhizomes and the rhizome biomass has a peak at 10-20 cm; thus, this species was more likely exposed to the highly concentrated oil that persisted in the root cavities along the rhizomes. Some of the black oil observed in the cores occurred along rhizomes, which were partially hollow and dead. Roots and rhizomes in the soil would grow until they encountered zones of oil that would slow growth and could eventually lead to death. *Spartina alterniflora* has about an equal proportion of roots to rhizomes and the rhizomes are smaller, so any reductions in the biomass of the rhizomes may have had a lesser effect on the overall belowground biomass. Alternatively, the lower belowground biomass of *Spartina alterniflora* may be in less contact with the oil.

This study showed that marshes can grow in oiled soils, but there can be long-term sublethal effects than can reduce overall health and productivity of the marsh ecosystem.

Deepwater Horizon, Northern Gulf of Mexico, 2010

Intensive Treatment of Thick and Persistent Oil
During the *Deepwater Horizon* oil spill, the heaviest oiling conditions were observed in the salt marshes of Northern Barataria Bay, Louisiana. These marshes are dominated by smooth cordgrass (*Spartina alterniflora*) and to a lesser degree needlegrass rush or black needlerush (*Juncus roemerianus*). Following spill source control and the completion of nearshore on-water oil recovery and bulk oil removal from many shoreline areas, persistent oiling conditions in the marshes of Northern Barataria Bay included a 5-10 m wide band of heavily oiled vegetation mats (aboveground vegetation laid over by oiling, which died but remained rooted in place) and wrack lines that in some cases overlaid a thick (>1 cm) layer of continuous emulsified oil (mousse) on the marsh substrate (Figure 4-2) (Zengel and Michel 2013; Zengel et al. 2015). Much of the mousse layer averaged 2-3 cm in thickness under the oiled vegetation mats and was typically heaviest under the oiled wrack line, to 5-8 cm thick. This oiling was persistent, with little appearance of further weathering or degradation over time. Subsurface oiling conditions were also observed, including burial of oiled vegetation mats or the underlying mousse layer by fine sediments or organic detritus. Instances of oiled crab burrows or oiled shoot/root channels were also observed. There were 73 km of heavier persistent marsh oiling documented across the response area, much of it in Northern Barataria Bay (Nixon et al. 2016).

Due to the degree and nature of persistent oiling in Northern Barataria Bay, several more common marsh treatment methods, including passive use of sorbents, low-pressure ambient flushing, vacuum treatments, and natural attenuation, did not appear to be effective for these heavily oiled shorelines. In addition, there was concern that long-term oiled marsh recovery over contiguous areas could be at risk without some form of effective intervention. There was also the significant competing concern that aggressive cleanup in the marshes could cause further damage, delaying or limiting oiled marsh recovery, including worsening marsh erosion, a major concern in the region. Due to these factors, a series of marsh treatment field tests were conducted under the response, followed by periodic monitoring (Zengel and Michel 2013; Zengel et al. 2015).

Figure 4-2. Heavy marsh oiling conditions in Northern Barataria Bay, Louisiana after the *Deepwater Horizon* oil spill. (left) Oiled vegetation mats and wrack. (right) Detail of the 2-3 cm thick mousse layer (orange color) beneath the oiled vegetation mats. Photo credit: Scott Zengel (from Zengel et al. 2015).

The initial treatment tests and short-term monitoring ruled out several potential treatments and combinations of treatments due to ineffectiveness, including cutting alone; raking alone; raking and cutting with weed trimmers; raking and flushing; raking, application of two different shoreline cleaning agents (PES-51 and Cytosol), and flushing; and raking and vacuuming. Tailgate testing of in situ burning was also deemed ineffective and potentially detrimental due to limited and incomplete oil combustion (Zengel and Michel 2013). The treatment tests further supported the cancellation of some on-going operational treatments, due to ineffectiveness and potential damage to the marsh. A second round of adaptive treatment tests followed by short-term monitoring indicated that a combination of manual raking and cutting with long-handled power hedge trimmers effectively removed the oiled vegetation mats and wrack, reduced the mousse layer, and resulted in the predominance of weathered surface oil residue, rather than mousse, on the marsh surface, without obvious detrimental effects to the marsh (Zengel and Michel 2013; Zengel et al. 2015). In this case the oiled vegetation that was raked and cut was predominantly dead, including the belowground roots and rhizomes, so damage to live vegetation was not a concern. During testing, the power hedge trimmers were surprisingly effective, whereas string trimmers or “weed whackers” could not cut the tarry matted vegetation, even when used with metal wire and spinning blade attachments. The hedge trimmers also appeared safer for workers as there were no projectiles and no spraying of oil during treatment.

Additional monitoring confirmed the changes in oiling conditions observed over the short term and indicated that the manual raking and cutting treatments aided the early stages of marsh vegetation recovery, as well as initial recovery for some marsh fauna such as fiddler crabs, as compared to the other treatments and natural recovery (no treatment) (Zengel and Michel 2013; Zengel et al. 2015). In addition, subsurface oiling assessments and sediment sampling indicated that oil was not mixed into the underlying sediments by the manual treatments, as has frequently been observed during past oil spills. Limited sediment sampling also showed evidence that manual raking and cutting treatments improved the rate of oil weathering in the marsh sediments. Monitoring also indicated that storm-driven oil remobilization from the marsh surface and subsequent marsh oiling and reoiling were minimized for the manual treatment areas, as compared to areas without treatment.

The treatment tests and short-term monitoring results were used to develop an operational-scale Shoreline Treatment Recommendation (STR) for Northern Barataria Bay based primarily on manual raking and cutting (Figure 4-3) (Zengel and Michel 2013; Zengel et al. 2015). The treatment sequence included removing oiled wrack with rakes and pitchforks (including cutting the tarry wrack into sections for removal, as needed), raking to lift and stand up the oiled vegetation mat and to spread the underlying mousse onto the standing dead vegetation, cutting the standing oiled vegetation with a power hedge trimmer for removal, additional raking where needed, scooping or scraping remaining thick mousse layers from the marsh surface with a variety of hand tools, and light raking and loose natural sorbent (bagasse) application as the workers backed their way out of the treatment area. All manual work on the marsh was conducted from walk boards, to limit further marsh damage from foot traffic and trampling.

STR adaptations over time included mechanical approaches that were developed and demonstrated in the treatment test area, following the same treatment sequence above (Zengel and Michel 2013). Operational mechanical treatments included floating barge and large airboat platforms positioned adjacent to marsh treatment areas and equipped with long-reach hydraulic arms coupled with attachments including grapples, rakes, cutting devices, scrapers, and rubber-edged “squeegees” to conduct marsh treatments (Figure 4-4). The “squeegee” devices were used to reduce thick mousse on the marsh surface after the heavily oiled wrack and vegetation mats were removed. Mechanical work was always followed by manual touch-up treatments.

Figure 4-3. Manual raking and cutting treatments for heavily oiled marsh in Northern Barataria Bay, Louisiana, following the *Deepwater Horizon* oil spill. Photo credit: Scott Zengel.

All intensive STR treatments in Northern Barataria Bay were conducted in the presence of SCAT/resource agency field advisors-monitors, to maximize treatment effectiveness and minimize marsh damage (Zengel and Michel 2013). STR treatments were implemented to completion over a seven-month period, with various adaptive revisions based on continued monitoring (including no treatment set-aside areas for comparison). Roughly 24 km of marsh shorelines were identified for potential treatment; and at least 11 km of marsh shorelines were documented as intensively treated in Northern Barataria Bay. 4,915 m^3 (6,429 cubic yards) and 536 tons of oil and oiled vegetation/debris were removed during treatments (not including material removed during subsequent monitoring and maintenance operations). Marsh treatment methods developed in Northern Barataria Bay were also adapted in several other locations across the area of response, usually over smaller continuous areas and limited to manual treatments. In total, approximately 27 km of marsh shorelines were identified for intensive cleanup treatment (Zengel et al. 2021; based on Nixon et al. 2016). In total, 71 km of oiled marsh shorelines were approved for treatment across the entire response area, including intensive and non-intensive treatments such low-pressure flushing, though the actual areas treated were likely less than this (Michel et al. 2013). Following operational-scale mechanical treatment across most of the treatment test area in Northern Barataria Bay (excluding the manual treatment and no treatment set-aside plots), experimental vegetation planting was conducted across ~400 m of shoreline in a new set of test plots established by Tulane University, working in coordination with the response (Bernik 2015; Zengel et al. 2015). Individual bare root smooth cordgrass

Figure 4-4. Mechanical treatments for heavily oiled marsh in Northern Barataria Bay, Louisiana, following the *Deepwater Horizon* oil spill. A) Raking of the oiled vegetation mat would gouge the marsh soils if done too deeply. Photo credit: Jeffrey Leonick. B) Flat “squeegee” used to scrape the thick oil for removal. C) Raking of the oiled wrack line had to be carefully guided to minimize removal of live vegetation. D) Grappling of the piles of oiled wrack was efficient and minimized foot traffic. Photo credit B-D: Jacqueline Michel.

stems were planted by hand at a planting density of ~2–3 stems per m^2 (or square yard) (Figure 4-5). Four varieties of smooth cordgrass were tested during planting, two transplanted wild stocks from Louisiana (one local "Bay Jimmy" variety and one non-local variety) and two nursery grown cultivars developed for Louisiana restoration projects. No fertilizer was used during planting. Based on structural vegetation metrics and erosion control, two varieties performed well, the local wild transplants from Bay Jimmy and the more common nursery-grown Vermilion cultivar (Bernik et al. 2021). These plantings did very well in the oiled and treated areas, rapidly increasing smooth cordgrass dominance, vegetation cover, and vegetation height in the plots. However, subsequent plantings of the Vermilion cultivar from containerized pots by others did not appear to do as well as the bare root plantings, at least qualitatively, and were not noticeable during subsequent monitoring events, perhaps because: 1) the containerized soils and plants may have had lower bulk density resulting in the plants being dislodged by storm waves, 2) the containerized plants were installed at lower densities, or 3) less desirable competing vegetation (especially seashore paspalum [*Paspalum vaginatum*]), had colonized prior to the later plantings.

Figure 4-5. Recently planted smooth cordgrass (*Spartina alterniflora*) after mechanical treatment in heavily oiled marsh in Northern Barataria Bay, Louisiana, following the *Deepwater Horizon* oil spill. Local Bay Jimmy wild transplants from bare root plantings are pictured in both photos. Photo credit: Scott Zengel.

Ongoing monitoring over several years indicated that both manual and mechanical treatments were effective at improving oiling conditions and aiding initial vegetation recovery (Zengel et al. 2015). However, mechanical treatments also had negative effects of mixing oil into the marsh soils and, in some cases, further worsening erosion beyond that caused by oiling impacts. Manual treatments appeared to strike the right balance between improving oiling and habitat conditions while not causing additional detrimental effects (Figure 4-6). Planting of local wild transplants following treatment further improved vegetation recovery and reduced shoreline erosion to background conditions. Longer-term monitoring revealed that planting continued to improve vegetation recovery and oil removal/degradation compared to cleanup treatments without planting (Zengel et al. 2021). Beyond two to three years, oiling levels and vegetation recovery for mechanical treatments without planting did not differ from natural recovery (no treatment), falling well short of vegetation recovery over five years. In contrast, within two years of planting, treatment areas were similar in dominant vegetation species composition and plant cover to reference conditions. Over the longer term, through eight years, planting was also effective in reducing oiled marsh erosion, with positive influences of planting extending beyond the immediate impacts of the oil spill on accelerated erosion rates (Zengel et al. 2022b).

Faced with comparable marsh oiling in the future, manual treatment followed by planting would be recommended. Selected mechanical methods would be useful to assist manual treatments. For instance, careful mechanical grappling from floating platforms adjacent to the marsh was effective and efficient for oiled wrack and oiled debris removal after manual raking and cutting, without further disturbing the marsh (whereas mechanical raking and scraping were too aggressive in some cases, at least in the absence of planting). It should be emphasized that the marsh oiling conditions treated in Northern Barataria Bay during the *Deepwater Horizon* oil spill included heavy and persistent thick oiling that killed much of the original vegetation prior to treatment. The intensive manual and mechanical methods used, including vegetation raking and cutting, would not be appropriate for most oil spills in marsh environments and, in many cases, could result in further marsh damage and limit marsh recovery. During the *Deepwater Horizon* spill response, only the most heavily oiled salt marshes were intensively treated—a small fraction (1-2%) of the 1,105 km of wetland shorelines that were oiled during the spill. Natural recovery was the preferred and appropriate approach for most oiled marshes. The no-treatment "set-asides" (oiled controls without treatment) and monitoring were essential for judging marsh treatment effectiveness and environmental effects and should be used when applying intensive or alternative treatment methods, including planting.

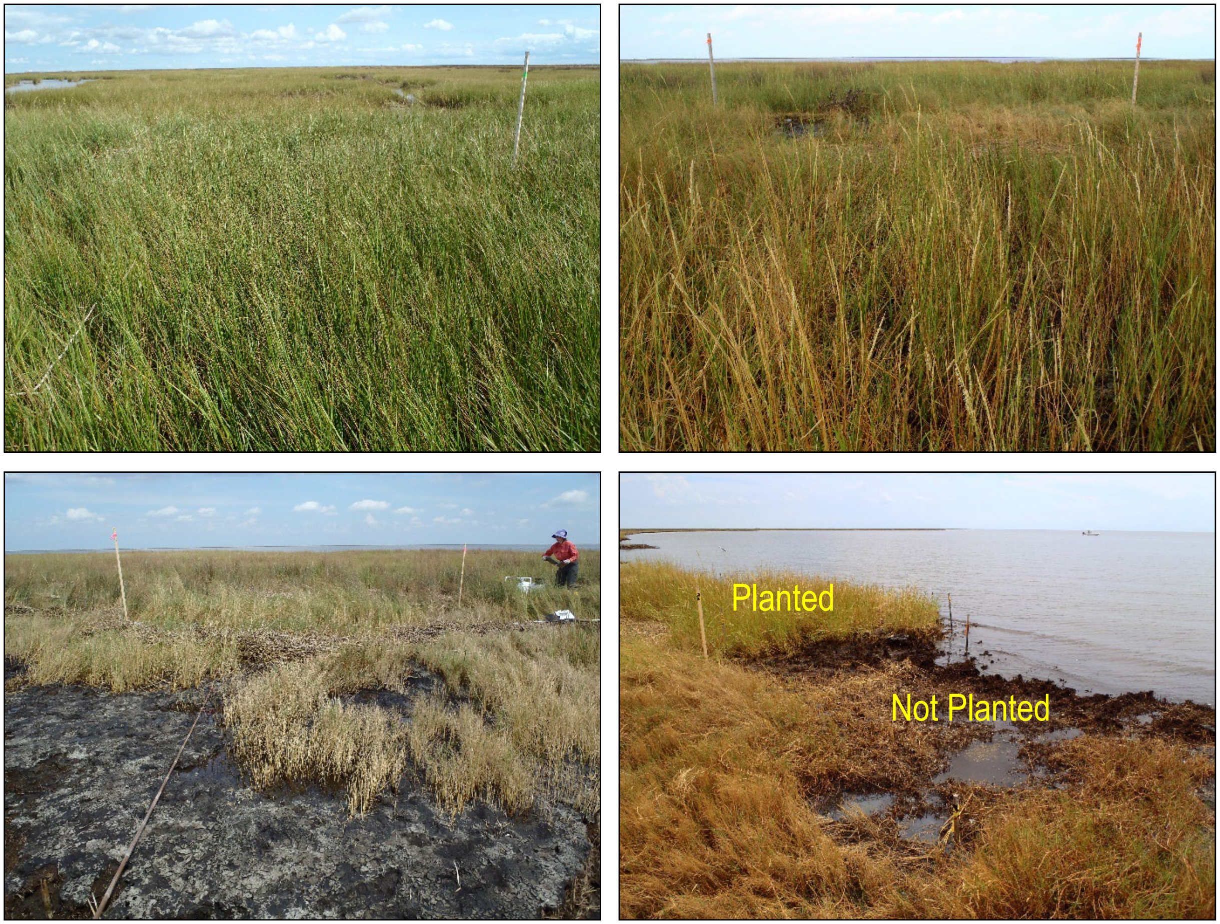

Figure 4-6. Summary of marsh conditions in 2012 in heavily oiled marsh in Northern Barataria Bay, Louisiana, following the *Deepwater Horizon* oil spill. Comparison of treatment types: A) reference site (intact healthy vegetation, *Spartina alterniflora*); B) heavily oiled site with manual treatment, showing *Spartina alterniflora* vegetation recovery in progress with pockets of thick oil and lower vegetation cover (upper left); C) heavily oiled site with natural recovery (no treatment), showing abundant thick residual surface oiling, low plant cover of different species composition (*Distichlis spicata* and/or *Paspalum vaginatum*), and stressed vegetation; D) heavily oiled site with mechanical treatment, with planting (upper left) and without planting (middle), emphasizing differences in plant cover, height, species composition (*Spartina alterniflora* versus *Paspalum vaginatum*), and shoreline erosion. Photo credit: Scott Zengel (from Zengel et al. 2015).

For Further Reading

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Appendix A. Summary of the literature on impacts of light refined oils on marshes.

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Spills					
T/B *Florida*, Buzzards Bay, MA Sanders et al. 1980; Teal et al. 1992; Peacock et al. 2005; Culbertson et al. 2007; 2008a;b	Sept 1969	No. 2 fuel oil/ 4,400 bbl	Salt marsh/ *S. alterniflora, Salicornia virginica, S. patens* No cleanup in marshes	2 yr: Vegetation dead in heavily oiled areas; Alive in lightly oiled areas 7 yr: Fiddler crabs recovering in some areas; Not in areas with elevated naphthalenes 30 yr: Moderately weathered oil present at 8,000 ppm at depths of 12-16 cm 40 yr: Oil residues impacting fiddler crabs, ribbed mussels, and marsh vegetation	2-40+ yr
T/B *Bouchard 65*, Buzzards Bay, MA Hampson and Moul 1978; Sanders 1978; Teal et al 1992; Hampson 2000; Peacock et al. 2007; Culbertson et al. 2007; 2008b	Oct 1974	No. 2 fuel oil/ estimated ~100 bbl released	Salt marsh/ *S. alterniflora, Salicornia virginica* No cleanup in marshes	3 yr: Complete mortality of vegetation and erosion rates 24x unoiled areas in heavily oiled marsh; Lightly oiled marsh showed lower biomass; Macroalgae disappeared, microalgal mat increased 17 yr: Vegetation slowly recovered; Eroded areas not recovered 30 yr: Weathered oil residues in surface sediments	, 3 -25+ yr

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Exxon Bayway, Arthur Kill, NY Burger 1994; Louis Berger and Assoc. 1991; Bergen et al. 2000	Jan 1990	No. 2 fuel oil/ 13,500 bbl	Salt marsh/ *S. alterniflora* No cleanup in marshes	0.5 yr: 7.6 ha of salt marsh killed; 2.8 ha recovering; Extensive fiddler crab and ribbed mussel mortality 3 yr: No recovery of most of the denuded areas, so replanted; Oil in sediments to 90 cm, at up to 55,000 ppm TPH 6-7 yr: Very little regrowth in unplanted area, no seedling survival; Planted areas mostly successful Unplanted areas not recovered due to erosion and geese grazing	3-7+ yr
T/B *North Cape*, South Kingstown, RI Michel et al. 1997; Wang et al. 2020	Jan 1996	Home heating oil/ 19,700 bbl	*S. alterniflora; not treated*	1.17 ha of fresh and low salinity salt marsh oiled, chlorosis observed about 10 days later; no differences in stem density, stem height, and biomass were found between post-spill and pre-spill *S. alterniflora* marsh plots after 6 mo	0.5 yr
Kinder Morgan Pipeline Spill, Suisun Marsh, CA USFWS and CDFG 2010	Apr 2004	Diesel/ 2,947 bbl	Diked marsh *Salicornia virginica,* Scirpus spp., Typha Extensive removal of oiled soils/fertilized/ tilled	0.3 yr: Heavily oiled area near pipeline break was tilled/fertilized; Vegetation along the channels showed good recovery; Initial high mortality of biota in channels	1-4 yr except the tilled area

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Field/Greenhouse Experiments					
North Greenland field oiling experiment Holt 1987	Aug 1982	Arctic diesel oil/ 10 L/m^2	Upland grassland, and three types of dwarf-shrub heath	3 yr: Dwarf-shrub heath showed no recovery; Graminoids showed almost no recovery except for *Carex bigelowii* which recovered moderately; Forbs showed only a few seedlings; Mosses showed good recovery in wet plots/no recovery in dry plots	>3 yr
Galveston Bay, TX Alexander and Webb 1985	Nov 1981; May 1983	No. 2 fuel oil/ 1 L/m^2 on soil, 1.5 L/m^2 on soil and lower plants, 2 L/m^2 on soil and entire plant	Salt marsh/ *S. alterniflora*	1 mo: 100% mortality at 2 L/m^2 and about 50% at 1.5 L/m^2 5 mo: Vegetation at 1.5 and 2 L/m^2 had ~50-99% mortality 12 mo: 1.5 and 2 L/m^2 lower vegetation biomass	1 yr for soil and lower stem oiling; 2 yr for higher and entire plant oiling
Galveston Bay, TX Webb and Alexander 1991	Sept 1983	No. 2 fuel oil/ 1 L/m^2 on soil, 1.5 L/m^2 on sediment and lower plants, 2 L/m^2 on soil and entire plant	Salt marsh/ *S. alterniflora*	3 d: Chlorosis when applied to vegetation, not soil 9 mo: Vegetation at 2 L/m^2 was mostly dead, regrowth from the edges of the plot; 12 mo: 2 L/m^2 treatment ~50% recovered, from rhizome growth from plants outside the plots; Other treatments slightly lower stem density than controls; No oil accumulation in soils	>1 yr; likely <2 yr
Greenhouse experiment, LA Lin et al. 2002	N/A	No. 2 fuel oil/ pre-mixed with soil at 10 doses from 0 to 640 mg oil/g soil	*S. alterniflora* culms	3 mo: Doses of No. 2 fuel oil as low as 29 mg/g significantly decreased belowground biomass; There was a strong dose-response relationship for biomass, stem height, stem density, evapotranspiration rate, and Microtox toxicity	N/A

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Greenhouse experiment, LA Lin and Mendelssohn 2009	N/A	Weathered diesel mixed at 7 doses from 0 to 456 mg oil/g soil	*Juncus roemerianus* culms	1 yr: Doses ≥160 mg/g reduced live stem density, ≥80 mg/g reduced stem height and above- and belowground biomass; Pots with plants had higher degradation of alkanes than those without plants	N/A
Jervis Bay, Australia Clarke and Ward 1994	N/A	Diesel/ 1 L/m^2	Salt marsh/ *Sarcocornia quinqueflora*, *Sporobolus virginicus*	1-12 mo: Near complete mortality and no growth of plants; New growth eliminated for up to one year; High mortality of *Littorina* snails, with limited recovery after one year; pulmonate snails recovered within one year	N/A

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Appendix B. Summary of selected light to medium crude oil spills and experiments in marshes.

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Spills					
T/V *Metula* Strait of Magellan, Chile Gundlach et al. 1982; Baker 1993; Owens et al. 1999; Gundlach 2017	Aug 1974	Light Arabian crude and Bunker C fuel oil/ 385,700 bbl	Salt marsh/ *Salicornia ambigua, Suaeda argentinensis* Not cleaned	1.5 yr: Thick mousse up to 30 cm on the marsh surface; no cleanup conducted 18 yr: Thick oil remains (mean of 4.1 cm, range up to 8 cm); little sediment on top; oil still soft and fresh looking; Little plant recovery, mostly small *Salicornia* rooted below the oil 23 yr: Most marsh still bare in areas with 10-15 cm oil; areas with thin oil layer (<2.4 cm) starting to revegetate; very small plots tilled in 1993 showed higher recolonization 40 yr: Recovered to an estimated 75% in interior marsh, to about 35% in outer marsh	18-40+ yr
T/V *Garbis* Florida Keys, FL Chan 1977	July 1975	Crude oil emulsion/ 1,500–3,000 bbl	*Batis maritima, Salicornia sp., Sesuvium portulacastrum, Monanthochloe littoralis, Borrichia frutescens;* *Not treated*	Plants killed by oil on stems, leaves, substrate; lightly oiled vegetation recovered after 6 months; unoiled vegetation was not impacted; seasonal recovery did not occur No epifauna survived oiling in the marsh; extensive substrate oiling and high temperature killed fiddler crabs but returned after 6 months; snails died due to isolation from water; other species survived	0.5 yr for lightly oiled only; no further monitoring of heavily oiled

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
T/V *Amoco Cadiz* Brittany, France Vandermeulen et al. 1981; Baca et al. 1987; Gilfillan et al. 1995; NOAA-CNEXO Joint Scientific Commission 1982	March 1976	Arabian and Iranian light crude/ 1.67 million bbl	Salt marsh/ Heavily cleaned (Also see case study in Chapter 4)	4 yr: Heavily oiled but untreated marsh recovered 7-8 yr: Heavily oiled untreated marsh recovered based on field data 12 yr: Heavily oiled treated marsh had less vegetated area and change in marsh community to low marsh because of excessive soil removal based on remote sensing data	4-5 yr not treated; 4-12+ yr intensively treated not treated
Ixtoc I, Bay of Campeche, Mexico Gundlach et al. 1981; Hooper 1981; Myer 1984	June 1979	Light crude/ 3.3 million bbl	Not treated	2 weeks: No severe damage to mostly lightly oiled fringing marshes (and mangroves) but scattered marshes with heavy oiling dead. 3 mo: Little to no impact to lightly oiled marshes and moderately oiled were still alive and growing; Heavily oiled marshes still dead after 3 months. September storm (Hurricane Allen) removed all but 0.04% of the oil	3 mo for light-moderate oiling; Unknown for small dead patches of heavily oiled marsh
T/V *Esso Bayway* Neches River, TX McCauley and Harrel 1981	Jan 1979	Light Arabian crude / 6,550 bbl	Salt marsh/ *S. patens* Flushing/ burning/cutting plots	7 mo: Flushed plots showed best recovery; burned and clipped plots showed little/no recovery Note: All plots were flooded continuously by high water during the study.	<1 yr for flushing; >1 yr for burn/cut

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Pipeline spill, Galveston Bay, TX Alexander and Webb 1987	Jan 1984	Light crude/ 6,720 gal	Salt marsh/ *S. alterniflora* Mostly not cleaned, affected 6.4 km	4-5 mo: Heavily oiled sites had plant mortality, little regrowth; up to 100 mg/g TPH; light-moderately oiled sites showed little effects 7-8 mo: Heavily oiled sites (10.5-18.3 mg/g TPH) had reduced densities of stems?; no oil visible in other sites 16 mo: Bare areas had 1-51 mg/g TPH 32 mo: Vegetation recovering but there were 2-3 m of erosion	>3 yr
Pipeline spill, Mississippi River, LA Hester and Mendelssohn 2000	Apr 1985	Louisiana crude/ 300 bbl	Brackish marsh/ *S. patens* *S. alterniflora* *Distichlis spicata* 20 ha heavy oiling, treated	1 yr: High mortality in 20 ha impacted area 4 yr: Nearly complete vegetative recovery, though some soil contamination still present	>4 yr
T/V *El Omar* Milford Haven, Wales Little et al. 1990	Dec 1988	Light Iranian crude/ 7,000 bbl	*Spartina sp.; not treated*	Marshes mostly self-cleaned by wave and tidal action within 9 months; no substrate oiling except post-spill when weathered oil initially captured in vegetation and seed heads of Spartina was buried in sediments with litter fall; heavily oiled areas took longer to recover	>1 yr
Fidalgo Bay, WA Hoff et al. 1993; Hoff 1995	Feb 1991	Prudhoe Bay crude/ 714 bbl	Fringing salt marsh/ *Salicornia virginica, D. spicata* Flushing, vacuum	16 mo: Foot trampling was most detrimental to vegetation, washing with vacuum most effective and minimized impacts to vegetation	0-2 yr not treated; 3-4 yr treated

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Gulf War oil spill Arabian Gulf Weaver et al. 2021; Barth 2002, 2007; Research Planning Inc 2003; Barth 2007; Höpner and Al-Shaikh 2008	Jan-Mar 1991	Kuwait crude oil/ 12.4 million bbl	Salt marsh/ *Arthrocnemum macrostachyum*, *Halocnemum strobilaceum*, *Salicornia europaea*, *Suaeda maritima, and scattered Avicennia marina*. No cleanup was conducted; extensive remediation conducted 2012-2014	10 yr: 25% of study sites showed no recovery at all; 20% fully recovered; 55% showing some recovery 16 yr: Continued evidence of recovery, mostly by crabs re-occupation of tidal channels 22 yr: Continued evidence of recovery, mostly in the lower marsh by annuals; very slow recovery of perennial vegetation in the upper marsh; remediation by re-activation or construction of new tidal channels speeding the rate of recovery 30 yr: Continued evidence of recovery, primarily in lower marsh, similar to previous results	10-30+ yr
Three pipeline spills, Pass a Loutre, Mississippi Delta, LA Lin et al. 1999	Jan 1993; Oct 1993; Jan 1994	S. Louisiana crude/ 1-12 bbl depending on site	Fresh water marsh/ *Phragmites australis* 500 gal: Intense cutting/flushing 210 gal: Light cleanup with sorbents 42 gal: No cleanup	1-2 yr: Intense cleanup site had very low soil TPH levels and full vegetation recovery; Light cleanup sites had elevated soil TPH and higher plant growth, indicating a stimulatory effect; No cleanup site (oil was contained within the boom for nearly 2 yr) had very elevated soil TPH and high plant mortality	<2 yr for cleaned area; >2 yr for no cleanup site

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
T/V *Sea Empress*, South Wales, UK Moore et al. 1997; White and Baker 1998; Bell et al. 1999	Feb 1996	Forties Blend light crude/ 490,000 bbl	Not treated	8 mo: *Halimione*, *Juncus maritimus*, *Triglochin maritimus*, and *Festuca rubra* present but often dead or dying; Annuals *Suaeda Salicornia*, and *Halimione* had greater damage in oiled areas 1 yr: Recovery limited to *Juncus* maritimus 20 mo: *Juncus* maritimus recovering, other perennials (*Puccinellia, Triglochin, Halimione)* sensitive and not recovered; Evidence of previous spills was also observed	1-6 yr
T/V *Estrella Pampeana*, Rio de la Plata, Argentina Moreno et al. 2004	Jan 1999	Patagonia Light crude/ 1,572 bbl	*Zizaniopsis bonariensis, Schoenoplectus californicus; not treated*	After 36 months, density and biomass declined in oiled plots. Areas with trapped oil (4 yr) recovered more slowly than areas without (<3 yr); Only cut (trampled) sites did not recover to vegetation cover at unoiled sites due to trampling and subsequent reoiling and damage to roots, rhizomes	2-4 yr
Mosquito Bay, LA (Williams pipeline) Michel et al. 2003	April 2001	Condensate/ 2,380–3,000 bbl	*S. alterniflora, S. cynosuroides, D. spicata* 4.9 ha of marsh oiled; 40 ha burned.	Vegetation killed by condensate was not recovered after 13 months; burn removed oil but did not mitigate toxicity impacts Plant shoots appeared after 1 week in lightly oiled, unoiled, and burned areas and was considered recovered; fiddler crabs present 6 months later, suggesting minimal residual impacts	<1 yr for light to moderate oiling; not recovered where vegetation killed by spill

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Deepwater Horizon LA Lin and Mendelssohn 2012; Silliman et al. 2012; Zengel et al. 2015; Silliman et al. 2016; Lin et al. 2016; Hester et al. 2016; Willis et al. 2016; Zengel et al. 2021; 2022a; 2022b	April-July 2010	Macondo-252 crude oil/ 4.1 million bbl	Salt marshes/ *S. alterniflora*; *J. roemerianus*	7 mo: Nearly 100% mortality in most heavily oiled marshes; moderately oiled areas also severely impacted; lightly oiled areas recovering, sometimes in a single growing season 1-4 yr: Lightly oiled and in some cases moderately oiled marshes recovered; heavily oiled marshes recovered more slowly with increases in erosion in most studies; recovery faster for *Spartina* than *Juncus*, leading to shifts in species composition in mixed marshes; marsh cleanup had variable results depending on methods used 7-9 yr: Recovery not complete in heavily oiled marsh; slow belowground biomass recovery may affect marsh resiliency, including in moderately oiled marsh.	10+ yr for heavily oiled marsh; 0-3 yr for lightly oiled marsh (limited data); 0-4+ yr moderately oiled marsh (limited data)
Field/Greenhouse Experiments					
Field/St. Louis Bay/MS De La Cruz et al. 1981	Late winter 1974	Empire Mix and Saudi Arabian crude 0.25-1.5 L/m^2 on marsh surface; and 1-10 repeated oiling of 0.6 L/m^2	Irregularly flooded tidal marsh/ *J. roemerianus*	3 mo: High (up to 14 mg/g) oil uptake in aboveground tissues 6 mo: Oil in tissues decreased to 2.5-4 mg/g 9 mo: Oil in tissues to background 12 mo: No oil in belowground tissues 1-7 mo: Reduced growth for all single oiling, with dose-response relationship; plant death for 1.5 L/m^2 and repeated oiling 3 yr: All plants regardless of oiling fully recovered	1 yr for 0.5-2 L/m^2; 2 yr for 2.4 L/m^2; 3 yr for 3.6-6 L/m^2

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Greenhouse/LA DeLaune et al. 1979	May 1976	S. Louisiana crude/ 4-32 L/m^2 maintain 5 cm water layer	Salt marsh/ *S. alterniflora*	4 mo: 4-8 L/m^2 reduced generation of new shoots because of persistent film on the water surface; at 16-32 L/m^2 no new shoots formed	N/A
Field/ Louisiana DeLaune et al. 1979	May 1976	S. Louisiana crude/ 1-8 L/m^2 added to 0.25 m^2 circular plots	Salt marsh/ *S. alterniflora*	4 mo: No significant difference in above-ground biomass harvested at end of the first growing season 16 mo: No significant difference in above-ground biomass harvested at end of the second growing season Note: oil did not come in contact with leaves	>1 yr
Field/Galveston Bay, TX Alexander and Webb 1985	Nov 1981; May 1983	Arabian and Libyan crude: 1 L/m^2 on soil, 1.5 L/m^2 on sediment and lower plant, 2 L/m^2 on soil and entire plant	Salt marsh/ *S. alterniflora*	1 mo: Live biomass reduced for oiling of entire plant and soil for both seasons 5 mo: Live biomass reduced for oiling of entire plant and soil for May application, not November 12 mo: Live biomass reduced for oiling of entire plant and soil for May application, not November	>1 yr for growing season / highest oiling
Greenhouse/North Carolina Ferrell et al. 1984	N/A	Venezuela crude (API =24)/ 100% on plants, 32 L/m^2 on water, both on plant/on water	Salt marsh/ *S. alterniflora* transplants in sand and 2 parts and 1 part marsh soil	3 mo: 100% oil on plants increased mortality and decreased stem density, aerial dry weight, and regrowth; Regrowth completely inhibited for treatments with oil on the water; Better regrowth in sods with marsh soils vs. sand	N/A

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
		20 cm on plants, 32 L/m^2 on water, both on plant/on water	Brackish marsh/ *S. cynosuroides* transplants in sand	3 mo: 20 cm oil on plants had no effect mortality, stem density, aerial dry weight, and regrowth; Oil penetration into the soil caused ~50% mortality and reductions in stem density, aerial dry weight, regrowth, and root mass	N/A
Greenhouse/LA Lin and Mendelssohn 1996	Aug 1991	S. Louisiana crude/ Up to 24 L/m^2	Fresh marsh/ *Sagittaria lancifolia*	1 yr: Significant increase in biomass and stem density Note: oil did not come in contact with leaves, oil was mostly in the soil	0 yr
Greenhouse/LA Lin and Mendelssohn 1996	Aug 1991	S. Louisiana crude/ >8 L/m^2	Salt/brackish marsh/ *S. alterniflora* *S. patens*	1 yr: No regrowth of biomass at levels of 8-24 L/m^2 Note: oil did not come in contact with leaves, oil was mostly in the soil; *S. patens* showed more short-term impacts compared to *S. alterniflora*	N/A
Greenhouse/LA Lin and Mendelssohn 2012	Nov 2010	Macondo-252 crude oil (weathered)/ 0-100% of shoot height oiled; 70% with repeated oiling every 4 d for 2 mo; 8 L/m^2 to soil surface	Salt marshes/ *S. alterniflora*; *J. roemerianus*	7 mo: For *S. alterniflora* effects persisted for the 70% repeated oiling and soil oiling only, even 100% oiling recovered to the level of the controls; For all metrics, *J. roemerianus* showed higher mortality at lower oiling exposures, starting at higher than 30% oiling	<1 yr for single dose to *Spartina* longer for *Juncus*

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Greenhouse/ AL Anderson and Hess 2012	Jul 2011	S. Louisiana crude (fresh, weathered 3 d; 3 weeks)/ 6 L/m^2, 12 L/m^2, 24 L/m^2 to soils with simulated tidal flushing	*J. roemerianus*	2.5 mo: TPH in soils for the 3 loadings were 13.3 ± 1.6, 25.0 ± 3.1, and 48.0 ± 16.1 mg/g; live stem counts reduced to 5-25% of controls; photosynthesis rate = 50% of controls–no differences with degree of weathering; Roots died and did not regrow	N/A

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Appendix C. Summary of selected heavy fuel oil spills and experiments in marshes.

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Spills					
T/V *Arrow* Chedabucto Bay, Nova Scotia Thomas 1973; 1978; Gilfillan and Vandermeulen 1978	Feb 1970	No. 6 fuel oil/ 71,425 bbl	Salt marsh/ *S. alterniflora* The heavily oiled cove was not cleaned	<u>2 yr</u>: Extensive vegetation mortality, due in part to chronic re-oiling; heavy mortalities of soft-shell clams <u>6 yr</u>: Continued differences in biomass between oiled and control stations; soft-shell clams and periwinkles also affected	6-8+ yr
Mill River, CT Burk 1977	Jan 1972	Heavy fuel oil/ unknown volume	Freshwater ponds/ 23 species No information on cleanup methods	<u>0.5 yr</u>: Annual vegetation severely affected, with disappearance of 7 species and declines in 3 species post-spill <u>3 yr</u>: Annual species recovering, particularly in high marsh <u>4 yr</u>: High and mid marsh communities recovered; low marsh still showed low species richness and diversity	>4 yr

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
T/V *Golden Robin* Dalhousie, New Brunswick, Canada Vandermeulen and Jotcham 1986	Sept 1974	Bunker C/ 1,000 bbl	High salt marsh/ *S. alterniflora* *S. patens* Various cleanup methods attempted	0.75 yr: First attempts to clean heavily oiled marsh, using manual removal of oiled vegetation, digging and spading of soils and vegetation, mechanical plowing, sod cutting, and burning. None were successful, and mechanical methods greatly disturbed the soils 2-3 yr: Poor recovery of vegetation in all test plots; oil contamination to at least 10 cm and up to 20 cm; asphaltic layer 1-3 cm thick 3-10 yr: Gradual vegetation recovery, most rapid for plots with manual treatment or burning 11 yr: Most plots fully recovered vegetation; soils still contaminated; burial by clean sediment up to 15 cm	~ 10 yr
Barge *Nepco-140* St. Lawrence River, NY Alexander et al. 1981	June 1976	Bunker C/ 7,333 bbl	Freshwater marsh/ *Typha* Intensive cleaning and cutting	1 yr: *Typha* growth where oiled and cut was 75 cm taller than where not cut, but had no flowers 2 yr: *Typha* growth and flowering were normal (note the water levels were low after cutting, so the cut stalks were always above water)	<2 yr
Bolivar Peninsula, TX Webb et al. 1981	Oct 1977	No. 6 fuel oil/ 1,000 bbl	Salt marsh/ *S. alterniflora/* Several hectares/ Cleanup by raking and vegetation cutting	7 mo: Full recovery by the first growing season; total plant coverage caused death of the aboveground vegetation; when the upper 1/3 was not oiled, plants survived	<1 yr

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
T/V *Lang Fonn* Potomac River, MD Krebs and Tanner 1981	Dec 1978	No. 6 fuel oil up to 10 cm in a small cove/25,000 gal	Salt marsh/ *S. alterniflora*/ Cleanup by raking and vegetation cutting	~2 yr: Vegetation mortality and no regrowth in soils with >16,000 ppm TPH, reduced growth at 5,000 ppm, and stimulation at <2,000 ppm; periwinkles and ribbed mussels much reduced	>2 yr
Barge *STC-101*, Chesapeake Bay, VA Hershener and Moore 1977	Feb 1976	No. 6 fuel oil 600 bbl	Salt marsh/ *S. alterniflora*/ Manual oil removal and vegetation cutting	3 mo: High mortality of periwinkles, slight mortality of ribbed mussels, no impact to oysters, new shoots shorter 7 mo: Periwinkles similar to controls, higher mortality of oyster spat in oiled marsh, and vegetation had higher stem density, shorter stems, and more flowering that showed an increase in net productivity	1 yr
Cape Fear River, NC Baca et al. 1983; 1985	April 1982	Heavy fuel oil 9,525 bbl	Riverine brackish marsh/ *S. alterniflora, S. cynosuroides, Scirpus olneyi, Juncus effuses*/ limited cutting	2 mo: 48 km of marsh shoreline was oiled; initial mortality of heavily oiled fringing vegetation; less mortality when only the lower parts of the plants were oiled 2 yr: All vegetation that was not cut was fully recovered and even increased in width; cut vegetation died with no re-growth	<2 yr
T/V *Julie N* Fore River, ME Michel et al. 1998	Sept 1996	IFO 380 and No. 2 fuel oil 4,050 bbl	Salt marsh/ *S. alterniflora S. patens*/ 10.2 ha/ No active cleanup	1 yr: All plots had stem heights and density similar to unoiled controls, but there were 96 patches of dead vegetation, likely from exposure to the No. 2 fuel oil	1 yr except for 96 patches

Spill Name/ Location/Citation	Oiling Date	Oil Type/ Volume Spilled	Habitat/Species/ Cleanup Method	Results by Years Post-spill	Years to Recovery
Lake Wabamun, Alberta, Canada Wernick et al. 2009	Aug 2005	Bunker C 937 bbl	Freshwater lake, *Schoenoplectus tabernaemontani (= Scirpus validus)*/reed cutting, vacuum	2 yr: Post-spill transect length, total cover, and biomass were not significantly different between exposed and reference lake basins, except for a few areas with reduced biomass, likely due to treatment effects	<2 yr
M/V *Westwood Anette*, Howe Sound, British Columbia, Canada Challenger et al. 2008	Aug 2006	IFO 380/ 180 bbl	Salt marsh / *Eleocharis palustris, Carex lyngbyei/* 4.2 ha/ Sediment removal, vegetation cutting	1 yr: Heavily oiled/not treated *Carex* had similar stem density/height and aboveground biomass to lightly oiled and unoiled controls; large reductions in these for sediment removal and trampling but not cutting only; For *Eleocharis*, in heavily oiled areas, areas that were flushed or cut showed positive effects; Very elevated TPH and PAH in trampled areas	N/A
Field/Greenhouse Experiments					
Georgia salt marsh Lee et al. 1981	Nov-Dec 1978	No. 5 fuel oil at 150 L over 4,000 m^2 (0.0375 L/m^2)	Salt marsh/ *S. alterniflora*	1.6 yr: High mortality of periwinkle snails; no change in populations of fiddler crab, oysters, or mussels; mud snails increased in density to scavenge on dead animals	>2 yr
Galveston Bay, TX Alexander and Webb 1985	Nov 1981; May 1983	No. 6 fuel oil: 1 L/m^2 on soil, 1.5 L/m^2 on sediment and lower plants, 2 L/m^2 on soil and entire plant	Salt marsh/ *S. alterniflora*	1 mo: Live biomass reduced by ~50% for oiling of entire plant only and May application, not November 5 mo: Dead biomass higher for both treatment with oil on vegetation and May application, not November 12 mo: No differences for oiled plots for all seasons and treatments	1 yr

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Appendix D. Spills and experiments where in situ burning was conducted in marshes.

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Intracoastal City Well Blowout or McCormick Well Blowout/ Intracoastal City, LA Castle 2012	Nov 1975	S. Louisiana waxy crude (pour point of 80°F)/110,000 bbl spilled/estimated 30,000 bbl burned Minor waxy residue was observed locally	Brackish marsh/ *Spartina* spp.	~70 ha, including area oiled by rainout of the blowout plume, heavily coating the plant canopy	Wetlands had been burned annually by trappers, and were due for burning at the time of the blowout. Observations of a test burn conducted by the USCG showed new growth after 1 week. Survey in April 1976 showed significant re-growth in burn areas except where berms and other earthworks were constructed	1-2 yr
Harbor Island, TX Holt et al. 1978	Oct 1976	Crude oil/377 bbl though only a small amount was burned	Salt marsh/ *S. alterniflora,* black mangrove	0.1 ha heavily oiled, burned by err	<u>0.5 yr</u>: *S. alterniflora* biomass = 60% of unoiled/unburned controls; Lowest recovery was in area of standing water; 100% mortality of mangroves in burn area	N/A but likely <2 yr
ESSO Bayway, Port Neches, TX McCauley and Harrel 1981	Jan 1979	Light Arabian crude/6,545 bbl small marsh islands burned in cleanup experiment	Brackish marsh/ *S. patens*	Small marsh island, with 3 plots of 3 m^2; flooded	<u>0.6 yr</u>: Biomass in oiled/burned was 3% of unoiled/unburned controls; Burned/unoiled biomass was 1.5% of unoiled/unburned controls; Poor recovery due to persistent high water levels (3-55 cm) and low salinity (~ 0 ppt) post-treatments	N/A but likely <5 yr
Trans-Alaska Pipeline, Fairbanks, AK Buhite 1979	Feb 1978	Prudhoe Bay crude/16,000 bbl spilled, 500 bbl burned	Ponded tundra with water depth from a few cm to 1 m	0.8 ha burned on Day 63	<u>0.5 yr</u>: Entire area was fertilized, with 50% plant regrowth during the first growing season	N/A but likely <5 yr

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Black Lake, West Hackberry, LA Overton et al. 1981	Sept 1978	Light Arabian crude/72,000 bbl spilled/most burned	Lacustrine and fringing marsh	N/A	Sediment samples collected at 1, 16, 29, and 53 weeks post-spill showed only background contamination. Foliage samples collected 1 and 16 weeks post-spill showed elevated PAHs from soot deposition several km from the site; At 29 weeks, foliage samples showed no contamination	N/A
Texaco Lafitte oil field Site 2, LA Mendelssohn et al. 1995	May 1983	S. Louisiana crude/ 282 bbl/some cleaned before burn	Brackish marsh/ *S. patens, D. spicata, S. alterniflora*	N/A	11 yr: No significant differences in soil TPH, live biomass, total biomass; Burned area higher species richness than unoiled control (7.6 vs 4.8), but not significant	N/A
Texaco Lafitte oil field Site 3, LA Mendelssohn et al. 1995	Sept 1986	S. Louisiana crude/ 4 bbl	Coastal brackish marsh/ *S. alterniflora, D. spicata*	N/A	8 yr: Soil TPH was 162 mg/g at the burn site vs 2 mg/g at the control site (may have been a more recent spill); No significant differences in live and total plant biomass and live-to-dead biomass; species richness in oiled/burned plots was 2.8 vs 6.6 in control plots; Overall recovery was ranked good	<8 yrs
Friendship II Pipeline, Kekcse, Hungary Nagy 1991	Jan 1988	Crude/ 2,657 bbl spilled/ 30 bbl burned	Peat and bog wetland (mostly sedges and reeds)	5.4 ha	1.5 yr: Sedge and reed vegetation recovered to near the original plant density	1.5 yr

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Imperial Oil, British Columbia, Canada Moir and Erskin 1994	June 1990	Canadian crude oil/ 840 bbl spilled/ majority burned	Freshwater wetland bog	2 ha burned on Day 2; bog was flooded	Day 5: New vegetation appeared; site was seeded and fertilized 0.75 yr: Vegetation was recovering and no oil was apparent on the site or stream	N/A
Pass a Loutre, Mississippi Delta, LA Mendelssohn et al. 1995	Aug 1990	S. Louisiana crude/several hundred bbl spilled/most burned	Freshwater marsh/ *Phragmites australis*	5.25 ha burned shortly after the spill	4 yr: Soil TPH was not different for oiled/burned vs 2 control sites; Live and total plant biomass and live:dead ratio were higher at the oiled/burned sites; overall recovery was ranked excellent	<4 yr
Chiltipin Creek, TX Gonzalez and Lugo 1995; Tunnell et al. 1995; Hyde et al. 1999	Jan 1992	S. Texas light crude/ 2,950 bbl spilled; 1,150 bbl burned; 80-85% burned Asphaltic, taffy-like residue covered the marsh surface and was manually removed	High marsh/ *D. spicata*, *Batis maritima*. *Borrichia frutescens*	6.5 ha burned on Day 4, 10 ha oiled; variable water levels	1.6 yr: High % cover but mostly by *D. spicata* 2.6 yr: Increase in species diversity, bare area declining; little change in TPH, but more weathered 3.6 yr: No change; apparent "steady state" 7 yr: Increase in bare area, species diversity but affected by drought and damage from feral hogs and seismic survey	Predicted 14-15 yr based on trajectory for climax species
Texaco Lafitte oil field Site 1, LA Mendelssohn et al. 1995	June 1992	S. Louisiana crude /1 bbl	Brackish marsh/ *S. patens, D. spicata, J. roemerianus*	N/A	2.4 yr: No significant differences in soil TPH, live and total plant biomass, or species richness for oiled/burned and control plots, but there was a trend towards lower biomass in the oiled/burned plots; Burned plots had higher live-to-dead plant biomass; Overall recovery was ranked as moderate to good	~2.5 yr

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Meire Grove, MN Amoco Pipeline Zischke 1993; Mendelssohn et al. 1995	Sept 1992	Fuel oil and gasoline. 2,500 bbl spilled/unknown amount burned	Freshwater wetland pond/ *Typha* spp.	0.8 ha burned on Day 2 of discovery, but leaked for 10 days	Shortly after the burn: # invertebrate taxa/m^2 was 18 times higher at control vs oiled/burned pond 1 yr: Considerable recovery in invertebrates 2 yr: Residual signs of trampling; Live plant biomass was 35 x higher and total plant biomass was 50 x higher in control pond vs oiled/burned pond; No differences in soil TPH; overall recovery was ranked poor	>2 yrs but likely <10 yr
Naval Air Station, Brunswick, ME Eufemia 1993; Metzger 1995	Mar 1993	JP-5 aviation fuel/ 1,512 bbl spilled/ 500 bbl burned No burn residue	Freshwater pond *T. latifolia, Sparganium americanum*	~1 ha burned on Day 8	0.4 yr: Studies of vegetation, fish, birds, mammals, benthic community, water quality, sediment quality oiled/burned vs control sites the following summer; No differences in plant cover or soil TPH; normal species abundance and distribution. Increase of *S. americanum* (burreed) over cattails, which was beneficial	<0.5 yr
Kolva River Basin Pipeline Spill Site 5, Komi, Russia Hartley 1996	1995	Crude oil/unknown volume because of multiple leaks from 1986-1994	Muskeg swamp with no outlet	6 ha burned	Burned violently for 20 hours, creating so much heat that the oil was driven deep into the peat mat; Burn residue on the surface was extremely viscous and oily, making further cleanup almost impossible	N/A but likely decades

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Rockefeller State Refuge, LA Hess et al. 1997; Pahl et al. 1997; 2003	Mar 1995	Condensate/40 bbl No burn residue	Brackish marsh/ *S. patens, D. spicata, S. alterniflora. Scripus robustus*	40 ha burned on Day 5; some water on marsh surface; Studied oiled, oiled/burned, and control transects	0.6 yr: Burned transects: total cover 50% of other treatments; *S. patens* 14% of other treatments; *S. robustus* much higher (*D. spicata* slowed by post-burn flooding), thus stem density 30% of other treatments; Soil TPH decreased to background 2.6 yr: Stem density, live biomass, total percent cover, and species composition of oiled/burned and oiled similar to control	3 yr
Refugio, TX Clark and Martin 1999	May 1997	Refugio Light and Giddings Stream crudes 90% burned Minor burn residue	Freshwater wetland/ *Borrichia frutescens*, *S. spartinae*	2.4 ha burned on Day 3	Observed new crayfish burrows shortly after the burn. Wetland was used for cattle grazing	N/A
Vermillion 16 Freshwater City, LA Henry 1997	July 1997	Condensate, API 50/ unknown amount spilled/most burned	Brackish marsh/ *Scirpus* spp, *S. patens, D. spicata*	3-4 ha burned on Day 13 after report; had been leaking 4 mo	During the burn, there was 5-10 cm of standing water in the thick vegetation 0.5 yr: Very little vegetation re-growth–the site looked like an open pond. Plant death attributed to the 4 mo of exposure to the light crude.	N/A

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Chevron Pipeline MP 68, Corrine, UT Williams et al. 2003 Michel et al. 2002	Jan 2000	Diesel/100 bbl 75-80% burned No burn residue	Freshwater wetlands, alkali flats, snow and ice cover	5.2 ha burned on 10 March, 1.3 ha on 27 April	Burn area = 1.3x intended area. Vegetation died in heavily oiled areas, burning not effective in removing oil penetrated into sediments or reduce toxic effects prior to burn; 4.1 ha fertilized and tilled in 2000/2001 to get PAH levels below criteria of 20 mg/kg	N/A. but likely <5 yr
Louisiana Point, LA Michel et al. 2002	Feb 2000	Condensate/ unknown amount spilled or burned; No residue	High salt marsh/ *D. spicata, Borrichia frutescens, Batis maritime, S. patens*	5.3 ha oiled, 55 ha burned on Day 3 0.5-1 cm water over marsh during the burn	0.6 yr: In burned areas, total cover 64% and stem density 22% of control, *B. frutescens* and *D. spicata* much reduced. Stem density lower for all species 1.6 yr: Total cover 76% and stem density 80% of control, with stem density of *B. frutescens* at 10%, *D. spicata* at 32%, and *Batis* at 120%	>1.6 yr, but likely <5 yr
Ruffy Brook, MN Michel et al. 2002	July 2000	Medium crude oil/>50 bbl 80% burned; tar-like residue ~1 cm thick, manually removed	Ponded freshwater wetland	1.2 ha burned on Day 1; 0.3-1 m of water in pond	1 yr: All herbaceous vegetation recovered; willows died (they are known to be sensitive to fire); No evidence residues sank	<1 yr

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Mosquito Bay, LA Michel et al. 2002	April 2001	Condensate/ >1,000 bbl; No residue	Brackish marsh/ *S. patens, D. spicata, S. cynosuroides*	4.9 ha oiled, 40 ha burned on Days 7 and 8; 1-10 cm water layer on marsh	After the burn, oil in burrows still present 0.5 yr: Burned/lightly and unoiled vegetation recovered with abundant fiddler crabs present, burned/heavily oiled areas along creek banks died, so did not reduce toxicity from contact with condensate prior to burn	<0.5 yr for lightly oiled areas; 1 yr for heavily oiled areas
Enbridge Pipeline, Cohasset, MN Leppälä 2004	July 2002	Canadian crude/ 6,000 bbl spilled, 3,000 bbl burned; significant residue that was thicker	Freshwater forested/ scrub-shrub with peat base	4.5 ha affected, 2.4 ha burned on Day 1, lasted 24 hours	Vegetation recovery was estimated to take many years because the deep excavation post-burn, as well as the burning of trees	Many years, likely >10 yr
Chevron Texaco #2 Tank Battery, Sabine NWR, LA Entrix 2003	Aug 2002	S. Louisiana crude/ 150-300 bbl; pockets of oil and oil residues with nets and sorbent materials	Brackish marsh/ S. patens, *Typha latifolia*	1.4 ha burned on Day 4	0.7 yr: 80-90% cover in burn area, slight hydrocarbon odor in sediments; Mean 2,150 ppm TPH 1.2 yr: Cattail 6 ft tall and seeds abundant, *S. patens* 3 ft tall; Mean 8 ppm TPH	1 yr
Chevron Pipeline MP 68, Corrine, UT Earthfax Engineering Inc 2003	Nov 2002	Gasoline No residue	Freshwater wetlands, alkali flats,	8.4 ha affected, 5.5 ha burned on Day 5	50% evaporated, 25-30% burned, rest in soils	N/A

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Chevron Empire, LA Myers 2006; Merten et al. 2008; Baustian et al. 2010	Oct 2005	S. Louisiana crude/100-200 bbl; Some burn residue that was sticky and liquid (unburned) oil in burrows; removed with sorbents and natural flushing	Brackish marsh/ *S. patens* *Schoenplec-tus americana* (chairmaker's bulrush), *D. spicata*	11 ha burned on Days 44-45 after the initial release during Katrina; 0-10 cm water over the marsh	30 d: New vegetation 30-60 cm high 0.75 yr: Plant biomass and species composition in oiled/burned returned to control levels; However, species richness remained somewhat lower in the oiled and burned areas compared to the reference areas; 1-1.5 yr: No differences between oiled/burned and control sites for sediment accretion, cellulose decomposition, and the rate of recovery from experimental disturbances (lethal and non-lethal removal of vegetation)	1 yr
Octave Header, Delta National Wildlife Refuge, LA Zengel et al. 2018; Michel and Zengel 2021	Nov 2014	S. Louisiana crude/100 bbl; No burn residue observed	*Phragmites australis*, tidal freshwater marsh	6.8 ha oiled, 2.3 ha burned Days 7 and 8; fire ended at the end of heavier oiling	90 d: Oil in soils in burned area initially elevated but decreased to background; vegetation cover reached reference sites, but different species; 1 yr: Total vegetation cover similar to reference and oil-and-not burned, but dominated by other species and a more diverse marsh assemblage; 2 yr: Total vegetation cover exceeded reference sites, still a mixed marsh assemblage	<1 yr

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
XTO Pipeline, Point a La Hache, LA Michel and Zengel 2021	Nov 2017	S. Louisiana crude/30 bbl; Water level over the marsh was 0-15 cm; Heavily oiled surface and subsurface sediments persisted in 280 m^2 around the release site	Intermediate marsh	1.4 ha oiled, 0.9 ha burned on Day 10; Residual oil and oiled vegetation was removed post-burn	Only visual observations of robust vegetation regrowth at 7 mo post-burn, except at the release site and heavily trampled areas	<1 yr except at release site and heavily trampled areas
Delta Farms pipeline release, Bayou Perot, LA; Michel and Zengel 2021	Dec 2017	S. Louisiana crude/50 bbl; Soils were saturated	Intermediate floating marsh, with *Eleocharis* sp., *Schoenoplectus* sp., and *S. patens*	0.23 ha oiled, 1.5 ha burned on Day 9; Site was hand raked over time to break up remaining oil	1 mo: Surface and subsurface oil trapped under the floating marsh remained; 9 mo: Vegetation cover and height recovered in the unoiled and burn sites; Oiled and burned vegetation recovering with new growth at the margins; 23 mo: Vegetation recovery at all sites except at release site	2 yr except at the release site
Dulac pipeline release, Lake Paige. LA; Michel and Zengel 2021	Nov 2018	Condensate/40 bbl; Soils were saturated	Freshwater floating marsh	0.14 ha oiled and burned on Day 4; no burn residue	No detailed observations	Unknown

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Time Energy pipeline release, Cox Bay, LA; Michel and Zengel 2021	Aug 2019	S. Louisiana crude/40 bbl (new release site 1) 1 bbl oil remaining psot-burn; and oil and produced water 1 month earlier at nearby site 2	Brackish marsh	0.36 ha oiled and burned on Day 6 of the new release site	7-8 mo: Site visits in Feb and Mar 2020 found oil droplets on the water in the site 1 burn area; 16 mo: Site visit reported that site 1 was recovering "well" but site 2 showed little regrowth due to continued impacts of high salinity produced water	Unknown
Field/Greenhouse Experiments						
Field/Texas Kiesling et al. 1988	?	No. 2 fuel oil/crude; Field experiment of flushing, cutting, burning	Salt marsh/ *S. alterniflora*	1m^2 field plots	1 yr: Biomass did not differ among treatments for both oil types; Burning increased oil in sediment by 27-72%	1 yr
Field/ Terrebonne Bay, LA Lindau et al. 1999	Aug 1995	S. Louisiana crude/ 2 L/m^2 Field experiment of oiled, oiled/burned, control	Salt marsh/ *S. alterniflora,*	2.4 m x 2.4 m plots, oiled stems and leaves	1 yr: No difference between oiled/burned, oiled, and control for plant density and biomass, carbon fixation; Stem height for burned plot was higher than others	1 yr
Field/ Terrebonne Bay, LA Lindau et al. 2003	Aug 1995	S. Louisiana crude/ 2 L/m^2 Field experiment of oiled, oiled/burned, control	Salt marsh/ *S. alterniflora,* Fresh marsh/ *Sag. lancifolia*	2.4 m x 2.4 m plots, oiled stems and leaves	0.25 yr: 83% reductions in carbon fixation, live stem density and plant height for oiled and oiled/burned vs. control; 1 yr: All oiled/burned plots had 100+% recovery compared to controls; Oiled plots were at 62% of controls	1 yr

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Greenhouse experiment/LA Smith and Proffitt 1999	April 1997	Venezuela crude, 0, 4, 8, 16, and 24 L/m^2 to the sediment surface	Three clones of *S. alterniflora*	Laboratory pots, oiled/ burned, oiled for 5 oil loadings; n=3 Water level at the sediment surface	0.5 yr: Oiled/burned had increased survival relative to oiled-only groups in all except the highest two oil dosages; At 16 L/m^2 oiled/burned, survival was slightly reduced; at 24 L/m^2, survival was 10-50%; New shoots died with >1 cm oil on the surface; For biomass, oiled/burned was higher than oiled for loadings of 4-16 L/m^2 oil, but all significantly decreased	N/A
Burn-tank experiments/ LA Mendelssohn et al. 2001; Lin et al. 2002	Aug 1999	Diesel 1.5 L/m^2	*S. alterniflora*	Laboratory pots, water depths 10, 2, 0, -10 cm (n= 5), burn duration 400 and 1400 s	0.6 yr: 10 cm water over the soil surface kept temperatures <37°C with high plant survival and regrowth; with 0 and 2 cm water, the soil temperatures were low, but diesel still killed the plants; water at 10 cm below the soil surface resulted in high soil temperature (120°C at 2 cm depth) and almost complete mortality; No plants survived at temperature >60°C at 2 cm soil depth; Burning did not remove oil that had penetrated into the soil	N/A

Spill Name/ Location/ Citation	Burn Date	Oil Type/Volume Spilled/Burned	Habitat/ Species	Burn Area	Results by Years Post-burn	Years to Recovery
Burn-tank experiments/ LA Lin et al. 2005; Bryner et al. 2003	Aug 2000	S. Louisiana crude and diesel 0.5 L/m^2 added to the soil before the burn (this dosage will not severely affect the plants but is high enough to analyze effectiveness of burning in removing oil from the soil)	*S. alterniflora S. patens/D. spicata, Sag. lancifolia*	Laboratory pots, water depths 10, 2, -2 cm (n= 5), burn duration 700 s	1 yr: 10 and 2 cm water over the soil surface kept temperatures at <40 and <50°C, respectively, with high plant survival and regrowth; Water at 2 cm below the soil surface resulted in temperature 80-100°C at 0.5 cm depth; *S. patens* and *D. spicata* survived 2 cm of soil exposure (dense stems, deeper rhizomes, and rapid regrowth), whereas *S alterniflora* (30% reduced survival) and *Sag. lancifolia* (50% reduction in survival) because its rhizomes are shallow); Burning did not remove the crude oil added to the soil before the burn; Burning did remove more of the diesel	N/A

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