

Oil Spills in Marshes

Planning and Response Considerations

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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 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 as much of the scientific literature and experience at 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 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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Oil Spills in Marshes

Planning and Response Considerations

Chapter 1. Marsh Ecology

Key Points

- Marshes are wetlands dominated by emergent herbaceous vegetation that are regularly, frequently, or continually flooded.
- Marshes are highly productive ecosystems that support a complex food chain of plants, microbes, and animals.
- Marshes vary widely in type 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 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 with water for extended periods of time or 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 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 services, including primary production, food web support, nutrient recycling, water filtration, sediment and storm water retention, shoreline stabilization, storm-surge protection, and soil development. Plate 1 and Plate 2 show representative plant and animal species in marshes.

Types of Marshes

Freshwater Non-tidal Marshes

Freshwater, non-tidal marshes are common, widespread, and diverse. They are similar in that they are dominated by grasses and sedges, 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, 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).

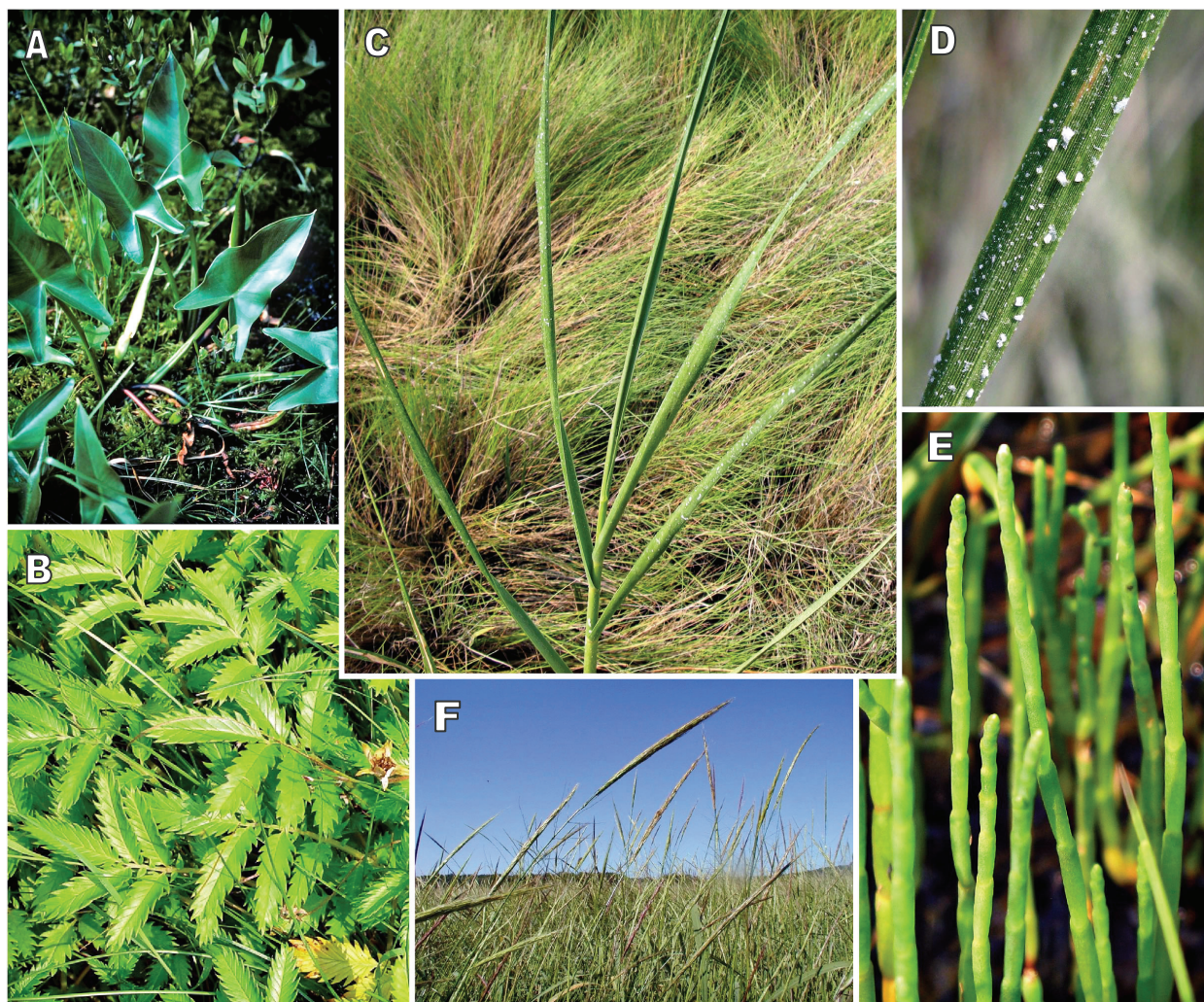


Plate 1: Representative marsh plants. All images reproduced with permission, with rights reserved. A: Green arrow arum (R.A. Howard, Smithsonian Institute). B: Pacific silverweed (Arthur Haines). C: Smooth cordgrass stem with salt meadow cordgrass behind (Sandy Richard). D: Salt crystals on smooth cordgrass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

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, 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 southwestern United States, particularly in northern Texas and 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 contains the largest single freshwater marsh system in the United States (Mitsch and Gosselink 1986). Although each of these systems has unique features, they share characteristic soils, vegetation, and wildlife.

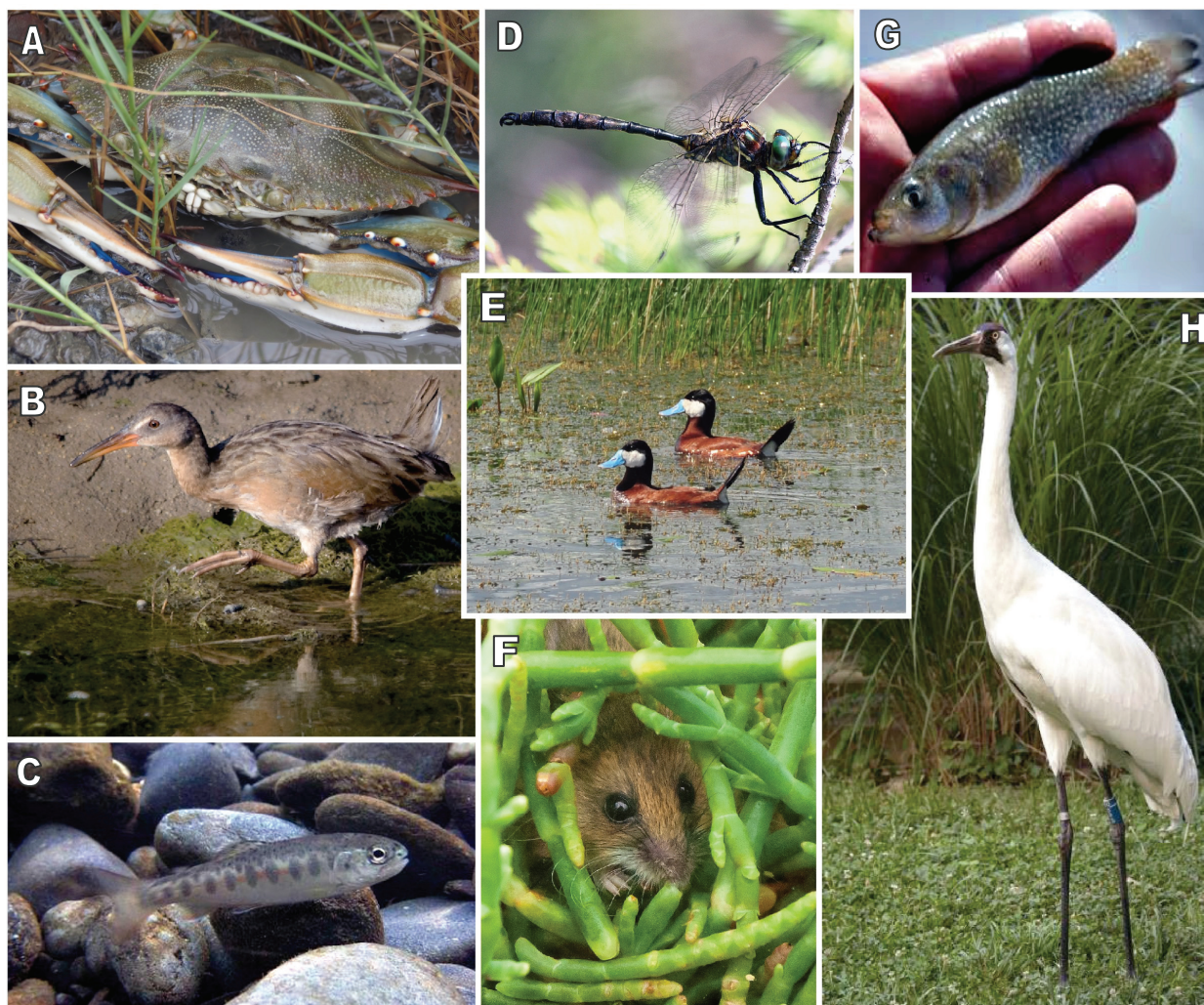


Plate 2: Representative marsh fauna. All images reproduced with permission, with rights reserved. A: Blue crab (Brian Henderson). B: Light-footed clapper rail (Nick Chill). C: Juvenile chinook salmon (NOAA). D: Hine's emerald dragonfly (P. Burton/USFWS). E: Ruddy ducks (Tom Koerner/USFWS). F: Salt marsh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

Soils in freshwater non-tidal marshes are typically alkaline, highly organic, mineral soils of sand, silt, and clay with high concentrations of calcium. 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 include common reed (*Phragmites australis*), prairie cordgrass (*Spartina pectinata*), wild rice (*Zizania aquatic*), and maidencane (*Panicum hemitomon*). Typical sedges include *Carex* spp., *Cladium* spp., and the bulrushes (*Scirpus* spp.). Other common plants include various rushes (*Juncus* spp.), cattails (*Typha* spp.), arrowhead (*Sagittaria* spp.), pickerelweed (*Pontederia cordata*), and horsetail (*Equisetum* spp.) (Mitsch and Gosselink 1986)¹.

¹ All plant names are from the USDA Plant Database (2013).

These marshes provide important habitat for migrating, breeding, and overwintering birds. According to Smith et al. (1964), in Tiner et al. (2002), over half of North America's waterfowl are produced in the prairie pothole region in an average year, while playas provide overwintering grounds for between 1 to 3 million birds, or greater than 90% of the region's waterfowl. Numerous species of reptiles and amphibians also depend on these habitats to breed and for refuge, as do many mammals, including muskrats (*Ondatra zibethicus*), weasels (*Mustela frenata* and *M. nivalis*), mink (*Mustela vison*), and raccoons (*Procyon lotor*) (Haukos and Smith 1992).

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.

Tidal Freshwater Marshes

Tidal freshwater marshes occur close enough to the coast to undergo daily changes in water levels driven by tides, but whose waters are fresh, with salinity 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, often 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).

Tidal freshwater marshes can be found on the Atlantic, Pacific, and Gulf coasts of North America, and are usually associated with large river systems (Leck et al. 2009; Mitsch and Gosselink 1986; Odum 1988). They are most extensive on the middle and southeast Atlantic coasts, northern Gulf of Mexico coast, and in Alaska. On the west 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 are found in San Francisco Bay Delta, Columbia River, and Puget Sound (Leck et al. 2009).

Sediments in tidal freshwater marshes typically contain clays, 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 to 40% organic matter, and west coast sediments ranging from 5% to around 60% (Thom et al. 2002; Josselyn 1983).

Tidal freshwater marshes are characterized by salt-intolerant plant species, typically a diverse community of emergent grasses, sedges, rushes, and herbaceous flowering plants. Typical plants in Atlantic coast tidal freshwater marshes include wild rice, cattails, and green arrow arum (*Peltandra virginica*), as well as pickerelweed, and broadleaf arrowhead (*Sagittaria latifolia*). 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. More birds use tidal freshwater marshes for breeding, nesting, rearing, and feeding than any other type of marsh. 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 salt water, while brackish and intermediate marshes experience irregular tidal flooding. The varying tidal regime influences the composition of the plant community found within each. 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 2-3 m on the East Coast, and in some areas of the West coast, greater than 3 m (Pennings and Bertness 2001; Seliskar and Gallagher 1983). Salt marshes have many adaptations to tolerate salt stress, as listed in Table 1-1.

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 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).

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 uptake by roots) High ion uptake (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

In contrast, the Pacific coast (excluding Alaska) has few large saltwater tidal habitats, contributing only 3% of the nation's salt marshes. 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 lagoon constituting less than 20% of the shoreline (Macdonald 1977).

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 (*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).

On the Pacific coast, smooth cordgrass 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 Virginia glasswort and saltgrass, but have no California cordgrass or turtleweed (Zedler 1982). Alkaligrass (*Puccinellia* spp.) and extensive stands of sedges (*Carex* spp., *Scirpus validus*, *Scirpus americanus*) and rushes are common (Macdonald 1977; Seliskar and Gallagher 1983).

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 cordgrass along the Atlantic and Gulf coasts. On the Pacific coast, 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.

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 an important role in the marsh food web. 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, especially 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 within a year. They germinate, flower, produce flowers, and die within one year. All of their roots, stems, and leaves die annually.

Perennials live for two or more years, overwintering and producing 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 above ground structures year round. Perennials can reproduce by seeds, but have evolved a variety of vegetative cloning strategies, including the production of bulbs, tubers, woody crowns, 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 east and Gulf coasts.

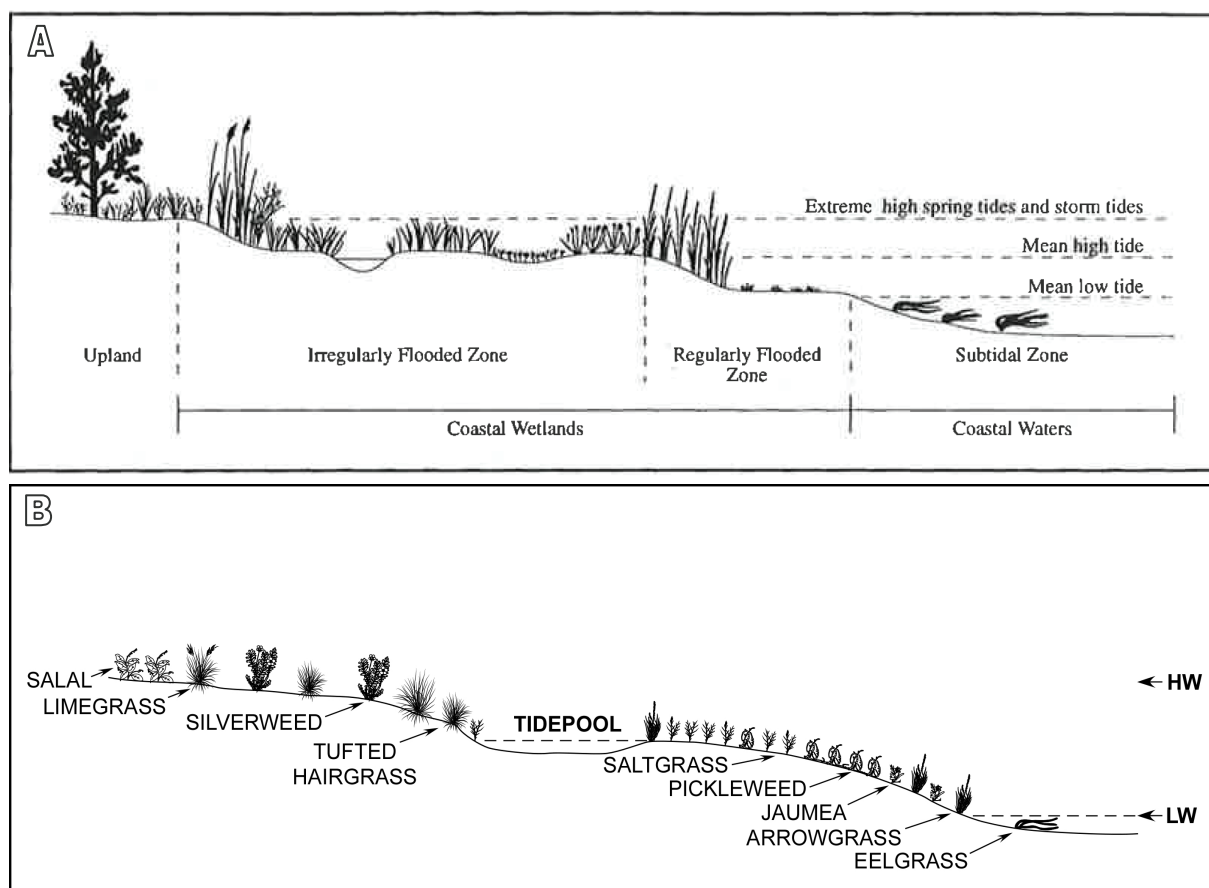


Figure 1-1. Tidal salt marsh zonation. A: Mid-Atlantic salt marshes based on frequency of tidal flooding. The low marsh is flooded at least one daily; the high marsh is flooded less often (from Tiner and Burke 1995). B: Typical zonation of marsh plants in a Pacific Northwest tidal salt marsh. The lateral 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 east and Gulf coast saltwater tidal marshes, grows 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 species important for and as 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/or 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, Yuma clapper rail, Hine's emerald dragonfly, and the whooping crane.

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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 are 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.
- The extent of oiling on the vegetation is a key factor. If only parts of the leaves are oiled, often the marshes 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, 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 gravity² 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 oil and refined products (Group 4 oils).

Light Refined Oil Products

Light refined products, such as gasoline, 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-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.

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 to 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

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 or stem density) that is comparable to uniled 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 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 Institute 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. The number of infaunal species was reduced by 92%. By 1991, Hampson (2000) reported that the 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).

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 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 communities.

Light to Medium Crude Oils

Light to medium crude oils 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; DeLaune and Wright 2011).

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. Those marshes with a thick layer of oil on the marsh vegetation and substrate died; those with moderate oiling appeared to be recovering (Lin and Mendelssohn 2012; pers. observation of the authors; 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.

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 (or not), and month of exposure, all of which influence how plants respond to oiling.

In summary:

- Crude oils can have both 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 often occurs quickly. These effects are reduced when oil weathers/emulsifies 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 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. Twelve 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 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 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. This lesson was learned again during the Bunker C spill from the M/V *Westwood* 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 *Phragmites* (Lin et al. 1999) and *S. alterniflora* (Krebs and Tanner 1981; Li et al. 1990). 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.

Hershener and Moore (1977) found 100% mortality of marsh periwinkles (*Littorina irrorata*) in the heavily oiled marsh and 80% reduction in abundance in the oiled marsh after two growing seasons. Periwinkle recovery is tied to vegetative recovery; juveniles are only able to settle and survive where there are stalks to climb and leaves in which to hide. Thus, penetration into and heavy contamination of marsh soils in a sheltered setting can result in impacts to salt marsh vegetation and communities for years.

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* 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/m² partial and 2 L/m² 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 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, either by thick layers on the surface or penetration into the soil;
- 3) The oil strands very quickly after spillage, thus there is relatively little weathering;
- 4) The entire plant surface is covered with oil during the growing season; or
- 5) 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) The oil undergoes extensive weathering or emulsification prior to stranding;
- 4) There is little to no contamination of the marsh soils; or
- 5) The oiled areas are exposed to waves or currents that speed natural removal rates.

In the next sections, the other factors influencing the degree of impact of oiling of marsh vegetation are summarized.

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 and the soil surface is covered with 1.5-2 L/m² of light refined oil, there is usually 100% mortality of the aboveground vegetation and sometime high mortality of the entire plant;
- 2) Similar coverage and loading by heavy refined oils and crude oils in greenhouse experiments result only in a slight decrease in aboveground biomass for a few months; and
- 3) At spills where at least the upper one-third of the aboveground vegetation remains unoiled, 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.

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. 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 crude oil. 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.

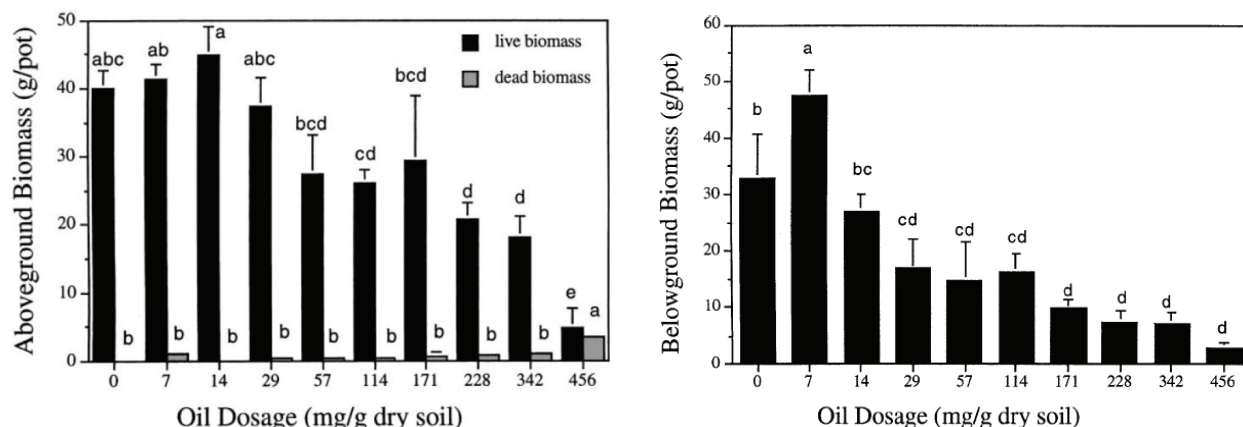


Figure 2-1. Effect of No. 2 fuel oil on the aboveground (left) and belowground (right) biomass of *S. alterniflora* three months after transplantation into soils mixed with different levels of oil. Values are means with standard errors (n=3). Means with the same letter are not significantly different.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

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 such 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 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 6.4 mg/g right after the spill, 15-66 mg/g three year later, and 2.4-22 mg/g five years later in areas still denuded of vegetation (Bergen et al. 2000).

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/m² of 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 thick mousse several centimeters thick was under a layer of thick oiled vegetative mat (see case study in Chapter 4). In fact, it was the lessons learned from the two 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 into

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 2-3A and Figure 2-3B).

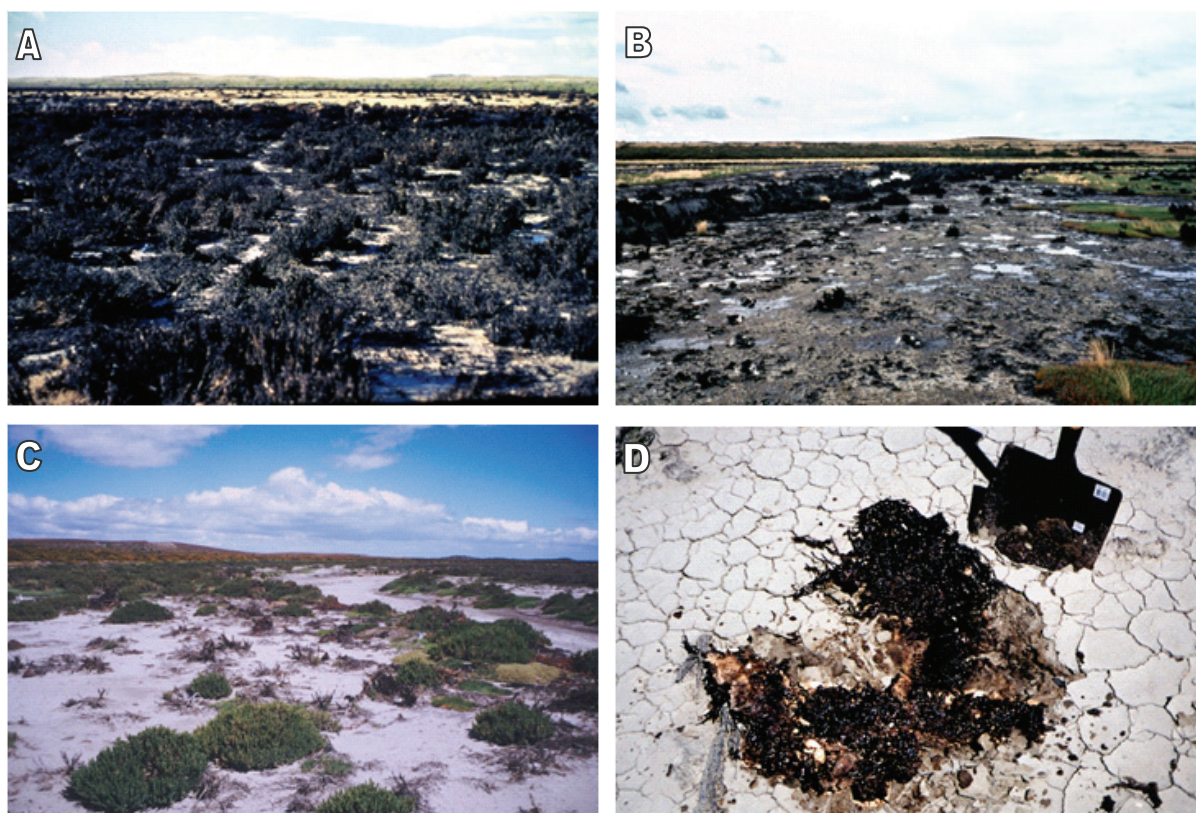


Figure 2-2. Examples of long-term persistent oiling in highly sheltered marshes. Punta Espora, Chile marsh that was heavily oiled as a result of the T/V *Metula* spill in 1974. A: Oiled marsh in January 1976. B: Same area in January 1981. The oil stranded on the high marsh platform where it is isolated 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 persisted for 21 years. Photo credit: Erich Gundlach.

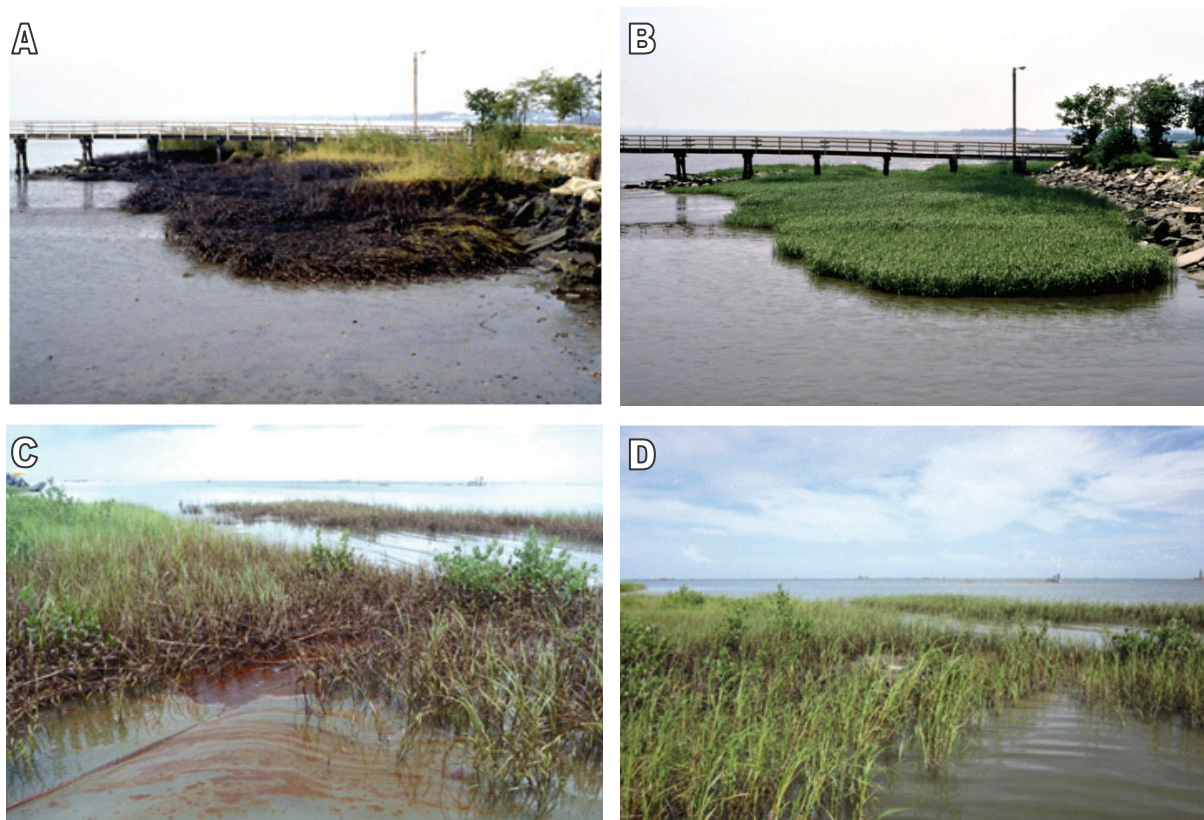


Figure 2-3. Examples of the role of natural removal processes. Relatively exposed marshes. Top Row: *Grand Eagle* spill in the Delaware River. A: 1984; B: 1986. Strong river currents and boat wakes were very effective at natural oil removal. Photo credit: Tom Ballou. Bottom Row: *Deepwater Horizon* oil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

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, 796 km of marsh shoreline in Louisiana were oiled; however, shoreline treatment was approved for only 71 km, or 8.9% of oiled marshes and associated habitats (with the actual distance treated being much lower than this) (Michel et al. 2013). One year later, there were 200 km of oiled marsh remaining. The bottom row of photographs in Figure 2-3 shows one 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 has 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.

Species Sensitivity

Marsh plants vary in their sensitivity by species and even by ecotypes within species (Lin and Mendelssohn 1996; DeLaune et al. 2003). When exposed under similar greenhouse experiments, the following species can be ranked from least to most sensitive:

Least Sensitive →

Sagittaria lancifolia

(bulltongue arrowhead)

Phragmites australis

(Roseau cane/common reed)

Typha latifolia

(Broadleaf cattail)

Spartina alterniflora

(smooth cordgrass)

Juncus roemerianus

(black needlerush)

→ Most Sensitive

Spartina patens

(saltmeadow cordgrass)



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 (A) and July 1997 (B), 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.

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 (that is, the oil has to come in contact with the soil surface). The size and number of stems may also be a factor, with smaller, more numerous stems per plant having the potential for a higher surface area of oiling. For example, *S. patens* can have ten times the number of stems per meter than *S. alterniflora*, which would provide a very large surface area for oil adherence.

It has generally been found that annuals are more sensitive than perennials. Annuals have to 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, often the annuals are the first to recolonize a heavily oiled marsh. 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 the impacted site, which can be relatively slow.

One result of the different sensitivities of plant species is that oiling can cause a temporary change in the composition of a marsh because of the dieback of the more sensitive species. However, eventually the normal species distribution returns, as long as other factors are 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 compete given the salinity regime and tidal elevation.

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 crabs, periwinkle snails, and mussels. High rates of mortality for fiddler crabs have been documented after spills of light refined oils. At the *Florida* spill in Buzzards Bay, Krebs and Burns (1978) documented that it took more than seven years for fiddler crabs to recover because of the persistence of the toxic naphthalene aromatic compounds in the soils in which the crabs burrow and the juveniles recruit. High fiddler crab mortalities were also reported for the Exxon Bayway spill of No. 2 fuel oil in Arthur Kill (Burger 1994), a crude oil spill in Nigeria (Snowden and Ekweozor 1987), 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 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 restoration projects along the Saudi Arabian coast are focusing on removal of the physical barriers to crab recruitment (Hale et al. 2011).

Periwinkle snails are also very susceptible to oiling impacts because they are closely associated with the emergent vegetation in the marsh, typically *S. alterniflora*. While vertical movement up and down cordgrass stems for feeding, predator avoidance, and regulation of temperature and oxygen availability is frequent, marsh periwinkles rarely move laterally more than a few meters (Vaughn and Fisher 1992). Both oil spill and experimental spill studies have observed high mortality of periwinkles immediately after a spill, followed by gradual increase in numbers over months or years as the vegetation recovers (Hershener and Moore 1977; Hershener and Lake 1980; Lee et al. 1981; Conan et al. 1982; Clarke and Ward 1994; Pearce 1996; Zengel and Michel 2012; Zengel et al. 2013).

Ribbed mussels are important to the survival of *S. alterniflora*, particularly along waterways with 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. They are also susceptible to smothering from oil or inability to recruit due to chronic toxicity.

Studies of resident Gulf killifish (*Fundulus grandis*) in marsh habitats and in laboratory studies with oiled sediments affected by the *Deepwater Horizon* oil spill (Whitehead et al. 2011; Dubansky et al. 2013)

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, delayed hatching, overall reduced hatching success, smaller size at hatching, and edemas. These fish have small home ranges and high site fidelity, making them particularly sensitive to population-level impacts from persistent oil exposures.

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 can reach 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, the oil spreads, disperses, and evaporates 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. Oiling of only the stems often results in limited mortality. If only the aboveground vegetation is 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 penetration, soils high in organic matter, and sites that are sheltered from natural removal processes.
- Vegetation recovery will occur quicker 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.
- 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 they are well planned and are 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 seventeen spills and field experiments, showing that sometimes treatment resulted in more rapid recovery, and sometimes treatment slowed recovery. Hoff