Oil Spills in Mangroves

PLANNING & RESPONSE CONSIDERATIONS

reprinted July 2010

U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration • National Ocean Service • Office of Response and Restoration

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Introduction

This report is intended to assist those who work in spill response and planning in regions where mangrove ecosystems are an important part of the coastline. By understanding the basics of the ecology of these forests and learning from past oil spills in mangroves, we can better plan for, protect, and respond to spills that may threaten them. Mangroves often border coastlines where coral reefs live offshore, and these two ecosystems are closely linked. Mangroves filter and trap excess sediment that could harm coral, and coral reefs protect shorelines where mangroves grow from excessive wave energy. Both habitats can be adversely impacted by oil spills, and spill responders must often consider tradeoffs between land-based and offshore resources during a response. This guide is a companion to *Oil Spills in Coral Reefs: Planning and Response Considerations*.

This is not intended to be a specific guide for choosing cleanup methods, as many comprehensive versions of these exist already. Rather, we summarize current research on mangroves from the perspective of those who may need to make decisions about response in mangroves and present the information in an accessible format for people with some science or response background. Experienced responders unfamiliar with mangroves may want background on mangrove ecology, while biologists may want an overview of oil toxicity and mangroves and response and cleanup applied to mangrove ecosystems. We have organized the topics by chapters, each of which can be read as a standalone, with additional references provided at the end of each chapter. A glossary defines specialized terms.

Chapter 1, mangrove ecology, provides an overview of mangrove forests, their associated communities, and how they respond to various natural and human stresses. Chapter 2, oil toxicity to mangroves, reviews the research available on oil toxicity and impacts to mangroves. In Chapter 3, we discuss general guidance for responding to spills in mangroves and provide specific considerations for cleanup measures. Chapter 4 discusses long-term recovery of mangroves from oil spill impacts and restoration techniques and approaches. Lastly, in Chapter 5 we have compiled several case studies that illustrate a range of issues from oil spills impacting various regions.

Though mangrove forests are in many ways very adaptable ecosystems, and are inherently able to respond to physical changes in their environment, they are highly vulnerable to oil toxicity and can be further damaged by many types of cleanup activities. Thus, we must approach any type of response or restoration activities in mangroves with knowledge and caution. The information in this document will, we hope, help to minimize environmental impacts in mangroves when oil spills threaten them.

Chapter 1. Mangrove Ecology

Mangrove – a tree or shrub that has evolved the adaptations for growing in the intertidal zone (specifically, adaptations to salinity and flooded conditions).

Key Points

- Mangroves worldwide cover an approximate area of 240 000 square kilometers of sheltered coastlines in the tropics and subtropics.
- Four of the most common ecotypes include fringe, riverine, basin, and scrub forests.
- Mangroves are restricted to the intertidal zone.
- Mangroves in general have a great capacity to recover from major natural disturbances.
- Mangroves maintain water quality by trapping sediments and taking up excess nutrients from the water.

What is a Mangrove?

Ecologically, mangroves are defined as an assemblage of tropical trees and shrubs that inhabit the coastal intertidal zone. A mangrove community is composed of plant species whose special adaptations allow them to survive the variable flooding and salinity stress conditions imposed by the coastal environment. Therefore, mangroves are defined by their ecology rather than their taxonomy. From a total of approximately 20 plant families containing mangrove species worldwide, only two, *Pellicieraceae* and *Avicenniaceae*, are comprised exclusively of mangroves. In the family *Rhizophoraceae*, for example, only four of its sixteen genera live in mangrove ecosystems (Duke 1992).

Where are Mangroves and What do They Look Like?

Mangroves worldwide cover an approximate area of 240 000 km^2 of sheltered coastlines (Lugo et al. 1990). They are distributed within the tropics and subtropics, reaching their maximum development between 25°N and 25°S (Figure 1.1). Their latitudinal distribution is mainly restricted by temperature since perennial mangrove species generally cannot withstand freezing conditions. As a result, mangroves and grass-dominated marshes in middle and high latitudes fill a similar ecological niche.

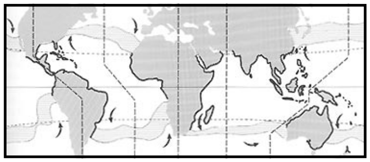

Figure 1.1 World map showing mangrove distribution zones. Dark lines show coastal areas where mangroves occur (N. C. Duke, American Geophysical Union).

The global distribution of mangroves is divided into two hemispheres: the Atlantic East Pacific and the Indo West Pacific. The Atlantic East Pacific has fewer species than the Indo West Pacific (12 compared to 58 species, respectively). Species composition is also very different between the two hemispheres. Out of a total of approximately 70 mangrove species, only one, the mangrove fern, is common to both hemispheres.

In the continental United States, mangroves are mainly distributed along the Atlantic and Gulf coasts of Florida (Figure 1.2). They also occur in Puerto Rico, the U.S.

Virgin Islands, Hawaii, and the Pacific Trust Territories. Craighead (1971) estimated a coverage of approximately 1,750 km^2 of mangroves along the Florida coast, with the highest development along the southwest coast. The Gulf of Mexico and Caribbean regions are characterized by low species richness, with only four dominant species: *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), *Laguncularia racemosa* (white mangrove), and *Conocarpus erectus* (button-mangrove or buttonwood). Black mangroves, however, can be found as far north as Texas, Louisiana, and Mississippi , indicating this species' greater tolerance to low temperatures and its ability to recover from freeze damage (Markley et al. 1982; Sherrod et al. 1986).

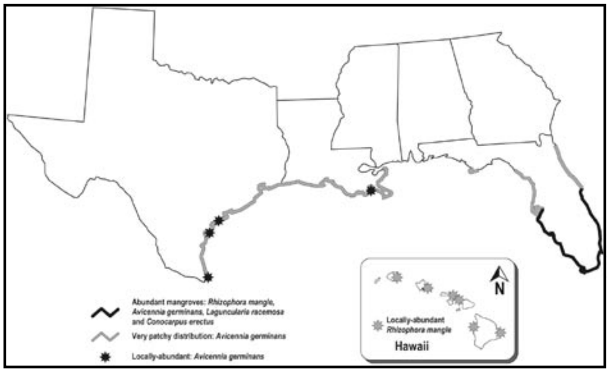

Figure 1.2 Mangrove distribution in the U.S. Gulf Coast (USGS).

Table 1.1 Common mangrove species with common and scientific names and general distribution.

Scientific name	Common name	Distribution
Acrostichum aureum	Mangrove fern	Both hemispheres
Rhizophora mangle	Red mangrove	Caribbean
*Avicennia marina**	Grey mangrove	Australia
*Avicennia germinans**	Black mangrove	Caribbean, FL, TX, LA, MS, American Pacific Coast
*Laguncularia racemosa**	White mangrove	Caribbean, American Pacific Coast
Conocarpus erectus	Button-mangrove or Buttonwood	Caribbean

* shown in Fig. 1.3a, b, c.

Figure 1.3a Conocarpus *(C.E. Proffitt).*

The California Current, which limits the northern extent of mangroves along the Pacific coast of the Americas, brings cold water as far south as Baja California. At the southern tip of this peninsula, mangroves are represented by an occasional, scrubby black or white mangrove. The mangroves of the Pacific Islands are represented by a very different assemblage of species belonging to the Australasian group. Some of the more characteristic genera include *Bruguiera*, *Rhizophora*, *Avicennia*, *Sonneratia,* and *Ceriops* (Tomlinson 1986).

Figure 1.3b Laguncularia Avicennia *(C.E. Proffitt).*

Mangrove Ecotypes

Mangroves colonize protected areas along the coast such as deltas, estuaries, lagoons, and islands. Topographic and hydrological characteristics within each of these settings define a number of different mangrove ecotypes. Four of the most common ecotypes include fringe, riverine, basin, and scrub forests (Lugo and Snedaker 1974; Twilley 1998). A *fringe forest* borders protected shorelines, canals, and lagoons, and is inundated by daily tides. A *riverine* forest flanks the estuarine reaches of a river channel and is periodically flooded by nutrient-rich fresh and brackish water. Behind the fringe, interior areas of mangroves harbor *basin* forests, characterized by stagnant or slow-flowing water. *Scrub* or dwarf forests grow in areas where hydrology is restricted, resulting in conditions of high evaporation, high salinity, low temperature, or low nutrient status. Such stressful environmental conditions stunt mangrove growth.

Each of these mangrove ecotypes is characterized by different patterns of forest structure, productivity, and biogeochemistry, all of which are controlled by a combination of factors such as hydrology (tides, freshwater discharge, rainfall), soil characteristics, biological interactions, and the effects of storms and other disturbances.

Life History

Mangrove Reproduction and Growth

Most mangroves are hermaphroditic (both sexes are present in an individual organism). Mangroves are pollinated almost exclusively by animals (bees, small insects, moths, bats, and birds), except for *Rhizophora*, which is primarily self-pollinated (Lowenfeld and Klekowski 1992). In most mangroves, germination takes place while the embryo is still attached to the parent tree (a condition called vivipary). The embryo has no dormant stage, but grows out of the seed coat and the fruit before detaching from the plant. Because of this, mangrove propagules are actually seedlings, not seeds (Figure 1.4).

Vivipary as a life history strategy helps mangroves cope with the varying salinities and frequent flooding of their intertidal environments, and increases the likelihood that seedlings will survive. Since most non-viviparous plants disperse their offspring in the dormant seed stage, vivipary presents a potential problem for dispersal. Most species of mangroves solve this problem by producing propagules containing substantial nutrient reserves that can float for an extended period. In this way, the propagule can survive for a relatively long time before establishing itself in a suitable location (McMillan 1971; Tomlinson 1988).

Buoyancy, currents, and tides disperse mangrove propagules and deposit them in the intertidal zone. Once established, the numerous seedlings face not only the stresses of salinity and variable flooding, but also competition for light (Smith 1992). These, in addition to other sources of mortality, cause very low survival rates for seedlings and saplings. Determining the age of mangroves is difficult, but flowering individuals have been recorded as young as 1.5 years old. Tree growth,

Hermaphroditic – Both sexes present in an individual organism.

Vivipary – The condition in which the embryo (the young plant within the seed) germinates while still attached to the parent plant (synonymous with viviparity).

Propagule – Seedling growing out of a fruit; this process begins while the fruit is still attached to the tree. For some species of mangroves, propagules represent the normal, tidally dispersed means of reproduction.

Figure 1.3c Avicennia *(C.E. Proffitt).*

Figure 1.4 Rhizophora *trees in Florida, with propagules (C. E. Proffitt).*

Evapotranspiration – The transfer of water from the soil, through a plant, and to the atmosphere through the combined processes of evaporation and transpiration. Evaporation is a function of surface area, temperature, and wind. Transpiration is a process of water loss through leaf stomatal openings, and is related to gas exchange and water transport within a plant. When the stomates open, a large pressure differential in water vapor across the leaf surfaces causes the loss of water from the leaves.

survival, and the ensuing forest structure are determined by the mangrove forests' ecotype.

There are few estimates of mangrove forest turnover (the time required for the forest to replace itself). Despite a precarious existence in the intertidal zone, Smith (1992) estimates mangrove turnover at 150-170 years. For comparison, estimates for turnover in lowland tropical rainforests is about 118 years (Hartshorn 1978).

Adaptations To Salinity

Mangroves can establish and grow under a relatively wide range of flooding and salinity conditions but are generally restricted to the intertidal zone where there is less competition with freshwater plants. Mangroves have developed a series of physiological and morphological adaptations that have allowed them to successfully colonize these environments.

Mangroves do not require salt water to survive, but because of poor competition with freshwater vegetation and unique adaptations to the intertidal zone, they are generally found under the influence of salt water. Salinity is mainly determined by local hydrology, where input of salt water comes from the periodic tides and fresh water comes from rivers, rainfall, groundwater, and runoff. High evapotranspiration (water loss through the soil and plant leaves) in the tropics and subtropics can increase salinity considerably, especially under environments with restricted water flow. Thus, salinity can fluctuate widely within mangrove forests, both over time and space.

Mangroves have evolved different mechanisms to tolerate high salinities: salt exclusion, salt secretion, and tolerance of high salt concentrations within plant tissues are the main strategies. Most mangroves have developed all three mechanisms, although to varying extents. *Rhizophora*, *Bruguiera*, and *Ceriops* have root ultrafilters that exclude salt while extracting water from soils (Rutzler and Feller 1996). In salt secretion, special organs or glands remove salts from plant tissues. For example, *Avicennia* and *Laguncularia* have special, salt-secreting glands that cause salt crystals to form on the leaf surfaces (Figure 1.5). These crystals then can be blown away or easily washed away by the rain. Leaf fall is another mechanism for eliminating excess salt in mangroves (Kathiresan and Bingham 2001).

Adaptations To Flooding

Mangrove forests are periodically flooded, with the frequency and magnitude of flooding determined by local topography combined with tidal action, river flow, rainfall, surface runoff, groundwater, and evapotranspiration. As with salinity, hydrology in mangrove ecosystems varies greatly in time and space, and mangrove species differ in their ability to tolerate flooding.

At the intertidal scale, the magnitude and frequency of flooding decreases in a landward direction. Mangrove species often show a distinctive distribution across this gradient, which is the basis for classifying mangroves by lower, middle, and upper intertidal zones. The lower intertidal zone represents an area inundated by medium-high tides and is flooded more than 45 times a month. The middle intertidal is inundated by normal high tides and it is generally flooded from 20 to 45 times a month. The upper intertidal zone represents areas flooded less than 20 times a month (Robertson and Alongi 1992).

Aerial roots – Roots that are formed in and exposed to air. In mangrove species (e.g., *Rhizophora spp*.), aerial roots develop into stilt roots (prop roots and drop roots) that anchor into the sediment, offering mechanical support and nutrient absorption.

Flooded conditions can decrease soil oxygen, impacting root tissues that need oxygen to metabolize, and toxic substances such as sulfides can accumulate. Mangroves have evolved special morphological adaptations to cope with this lack of oxygen. First, mangroves have shallow root systems to avoid the lack of oxygen in deeper soils. As a result, most of the root biomass is found above 70-cm soil depth (Jimenez 1992). In some species (*Avicennia*, *Laguncularia*), roots form an extensive network close to the soil surface. Other species (*Rhizophora*) form extensive aerial roots (prop roots and drop roots) that help stabilize the tree in unconsolidated sediments (Figure 1.6). Second, above-ground root tissue such as aerial roots (*Rhizophora*) and pneumatophores (*Avicennia*, *Laguncularia*) transport oxygen from the atmosphere to the root system.

Figure 1.5 Close-up of mangrove leaf showing salt crystals (C.E. Proffitt; Gulf of Fonseca, Honduras).

These specialized roots contain spongy tissue connected to the exterior of the root via small pores called lenticels. During low tide, when lenticels are exposed to the atmosphere, oxygen is absorbed from the air and transported to and even diffused out of the roots below ground. This diffusion of oxygen maintains an oxygenated microlayer around the roots that enhances nutrient uptake. The microlayer also avoids toxicity of compounds such as hydrogen sulfide that otherwise accumulate under such conditions.

Pneumatophore – A vertical extension of an underground root, with lenticels and aerenchyma to allow for gas exchange. Pneumatophores are characteristic of trees adapted to flooded conditions (such as *Avicennia spp*.).

Lenticel – A small, elliptical pore in the periderm that is a means of gaseous exchange.

Despite the harsh conditions under which mangrove forests develop, they can form highly diverse and productive communities. Riverine mangrove forests are recognized among the most productive ecosystems in the world, due in large part to low salinities, high nutrient supply, and regular flooding (Day et al. 1987). Less ideal conditions, such as hypersalinity or permanent flooding, severely limit mangrove growth and productivity; extreme conditions, such as restricted hydrology due to impounding, can kill many mangroves. Growth and productivity of mangroves thus ranges widely depending on the conditions under which they grow.

Defoliation – The removal of the foliar tissues of a plant, resulting from mechanical (e.g., hurricanes), biological (herbivore), or chemical agents (e.g., plant hormones).

Mangrove Mortality

Mangrove mortality from biological sources includes competition, disease, herbivory predation, and natural tree senescence. All developmental stages are affected, including propagules, seedlings, saplings, and trees. However, mangroves in early stages of development experience higher mortality rates and mortality is generally density-dependent. At the tree stage, smaller trees are at higher risk due to competition with larger trees for light and/or nutrients.

Figure 1.6 Rhizophora *tree (with man in branches) showing prop roots (C.E. Proffitt).*

Mangrove diseases include impacts from fungi that defoliate and kill black and red mangroves in Australia and Florida. Insects such as scales and caterpillars cause defoliation and, in Puerto Rico, beetles and other boring insects are known to kill mangroves. *Rhizophora* seedlings are especially vulnerable to mortality caused by the boring beetle. Crabs are important predators of propagules and are a major source of mortality at this stage. Differences in predation rates on seedlings of different mangrove species may eventually alter species dominance in the adult trees (Smith 1987). Overall, these various biotic disturbances have a relatively minor impact on the mangrove forest when compared with larger-scale environmental impacts.

In contrast with purely biological causes, severe environmental disturbances can inflict larger-scale mortality on mangrove forests. These disturbances include periodic frosts, and hurricanes and other storms, which bring heavy sedimentation (Jiménez and Lugo 1984). In spite of the drastic consequences of massive tree mortality, mangrove forests are generally able to recover.

Habitat Function

Shoreline Stabilization and Protection

Located along the coastline, mangroves play a very important role in soil formation, shoreline protection, and stabilization. The mangrove forest's extensive, above-ground root structures (prop roots, drop roots, and pneumatophores) act as a sieve, reducing current velocities and shear, and enhancing sedimentation and sediment retention (Carlton 1974; Augustinus 1995). The intricate matrix of fine roots within the soil also binds sediments together. Not only do mangroves trap sediments—they also produce sediment through accumulated, mangrove-derived organic matter. Mangrove leaves and roots help maintain soil elevation, which is especially important in areas of low sediment delivery, such as the southern coast of Florida. By enhancing sedimentation, sediment retention, and soil formation, mangroves stabilize soils, which reduces the risk of erosion, especially under high-energy conditions such as tropical storms.

Coastal protection is also related to the location of mangroves in the intertidal zone. Mangroves are able to absorb and reduce the impacts of the strong winds, tidal waves, and floods that accompany tropical storms, thereby protecting uplands from more severe damage (Tomlinson 1986; Mazda et al. 1997). Even though some of these forces can devastate the mangrove forest, mangroves in general have a great capacity to recover after major disturbances. Mangroves produce abundant propagules, their seedlings grow quickly, and they reach sexual maturity early—characteristics that accelerate their natural ability to regenerate. The speed of recovery, however, depends on the type of forest affected, the nature, persistence, and recurrence of the disturbance, and the availability of propagules.

Detritus – Non-living organic matter that is so decomposed that it is impossible to identify the original parent material.

Animal Habitat and Food Source

Mangroves provide both habitat and a source of food for a diverse animal community that inhabits both the forest interior and the adjacent coastal waters. Some animals depend on the mangrove environment during their entire lives while others utilize mangroves only during specific life stages, usually reproductive and juvenile stages (Yañez-Arancibia et al. 1988).

Mangroves' intricate aerial root system, which is most highly developed within the lower intertidal zone, provides a substrate for colonization by algae, wood borers, and fouling organisms such as barnacles, oysters, mollusks, and sponges. From the diverse group of invertebrates found in mangroves, arthropods, crustaceans, and mollusks are among the most abundant and have a significant role in mangrove ecosystems. As mentioned earlier, some species of crabs, recognized as propagule or seedling predators, can influence mangrove forest structure (Smith 1987), as may seedling predation by beetles or other insects. Crabs and snails, important components of the detritus food chain, help break down leaf litter through grazing.

Shrimp, an important fisheries resource, find food and shelter in mangrove forests. Likewise, commercially important bivalves such as oysters, mussels, and clams are commonly found in and around mangrove roots. Mangroves are also recognized as essential nursery habitat for a diverse community of fish, which find protection and abundant food in these environments, especially during juvenile stages.

Many animals found within mangroves are semi-aquatic or derived from terrestrial environments. Numerous insect species are found in mangrove forests; some play critical roles as mangrove pollinators, herbivores, predators, and as a food source for other animals (Hogarth 1999). Amphibians and reptiles such as frogs, snakes, lizards, and crocodiles also inhabit mangrove forests. Birds use mangroves for refuge, nesting, and feeding. In Florida and Australia, up to 200 species of birds have been reported around mangrove communities (Ewel et al. 1998). Most of these birds do not depend completely on mangroves, and use these habitats only during part of their seasonal cycles, or during particular stages of the tide. Mammals living in mangrove forests include raccoons, wild pigs, rodents, deer, monkeys, and bats. Finally, turtles, manatees, dolphins, and porpoises can be occasional visitors to mangrove-dominated estuaries.

Water Quality Improvement

Mangrove habitats maintain water quality. By trapping sediments in the mangrove root system, these and other solids are kept from offshore waters, thereby protecting other coastal ecosystems such as oyster beds, seagrasses, and coral reefs from excessive sedimentation. This process can also remove agrochemical and heavy-metal pollutants from the water, since these contaminants adhere to sediment particles.

Mangroves also improve water quality by removing organic and inorganic nutrients from the water column. Through denitrification and soil-nutrient burial, mangroves lower nitrate and phosphorus concentrations in contaminated water, preventing downstream and coastal eutrophication (Ewel et al. 1998). However, the potential of mangroves to "clean" water is limited and depends on the nature of the inputs, and the surface area and nutrient biochemistry of the mangrove forest.

Mangroves have also been used as a tertiary wastewater treatment (Twilley 1998). Even though this practice may increase mangrove productivity by providing nutrients, it should be conducted under carefully designed and monitored conditions. This will reduce negative impacts, such as contamination of adjacent waterways or introduction of invasive species.

Mangrove Economic Value and Uses

There are many mangrove products and services, not all of which are easily quantified in economic terms. Mangrove products can be obtained directly from the forest (wood) or from a derivative, such as crabs, shrimp, and fish. The most common uses of mangrove wood are as a source of fuel, either charcoal or firewood, and as the primary material for the construction of boats, houses, furniture, etc. Given these uses, commercial mangrove production (especially of *Rhizophora spp*.) is common around the world, primarily in Asia (Bandaranayake 1998).

Besides wood, other mangrove products have been exploited commercially. Mangrove bark has traditionally been used as a source of tannins, which are used as a dye and to preserve leather. The pneumatophores of different mangrove species are used in making corks and fishing floats; some are also used in perfumes and condiments. The ash of *Avicennia* and *Rhizophora mangle* is used as a soap substitute. Other mangrove extracts are used to produce synthetic fibers and cosmetics. Mangroves are also used as a source of food (mangrove-derived honey, vinegar, salt, and cooking oil) and drink (alcohol, wine). For example, the tender leaves, fruits, seeds, and seedlings of *Avicennia* *marina* and vegetative parts of other species are traded and consumed as vegetables (Bandaranayake 1998).

Mangroves have great potential for medicinal uses. Materials from different species can treat toothache, sore throat, constipation, fungal infections, bleeding, fever, kidney stone, rheumatism, dysentery, and malaria. Mangroves also contain toxic substances that have been used for their antifungal, antibacterial, and pesticidal properties (Bandaranayake 1998).

Mangrove forests have been widely recognized for their role in maintaining commercial fisheries by providing nursery habitat, refuge from predators, and food to important species of fish and shrimp. Demonstrating a statistical relationship between mangroves and fishery yields has proven difficult, however, because mangroves, seagrasses, and other nearshore habitats are closely linked, and all provide nursery habitat and food for fish (Pauly and Ingles 1999).

Mangrove ecotourism is not yet a widely developed practice, but seems to be gaining popularity as a nondestructive alternative to other coastal economic activities. Mangroves are attractive to tourists mostly because of the fauna that inhabit these forests, especially birds and reptiles such as crocodiles.

Figure 1.7 Aerial photo of mangrove forest showing hurricane damage in Guanaja, Honduras, taken 14 months after Hurricane Mitch (D.R. Cahoon and T.C. Michot).

Anthropogenic and Naturally Occurring Impacts

Storms and Hurricanes

Mangroves are particularly sensitive to storms and hurricanes because of their exposed location within the intertidal zone, their shallow root systems, and the noncohesive nature of the forest soils. The effect of storms and hurricanes varies, depending on factors such as wind fields and water levels. Small storms generally kill trees by lightning or wind-induced tree falling, creating forest gaps—an important mechanism for natural forest regeneration. Coastal sedimentation resulting from storms can also lead to mangrove forest expansion.

In contrast, high-energy storms (hurricanes and typhoons) can devastate mangrove forests. Entire mangrove populations can be destroyed, with significant long-term effects to the ecosystem (Figure 1.7; Jiménez and Lugo 1985). Mangrove forests that are frequently impacted by hurricanes show uniform tree height, reduced structural development and, sometimes, changes in species composition. However, mangrove forests can recover despite such impacts. How fast a forest recovers depends on the severity of

Eustatic sea level rise – The worldwide rise in sea level elevation due mostly to the thermal expansion of seawater and the melting of glaciers.

RSLR – relative sea level rise - The net effect of eustatic sea level rise and local geomorphophlogical changes in elevation. Local subsidence can make apparent RSLR much greater than eustatic rise.

Microtidal – A tidal range of less than one meter.

Deposition – The accumulation of material on a substrate. In mangrove systems this term is typically used in relation to accumulation of surface sediment.

mangrove damage and mortality, mangrove species composition, the degree of sediment disturbance and propagule availability.

Sea Level Rise

In response to global climate change, a gradual increase in sea level rise has been documented since the late Holocene (7000 YBP) and continues to the present. Estimated global rates of sea level rise (eustatic) have been estimated between 1 and 1.8 mm/yr^{-1} (Gornitz 1995). Local subsidence, uplift, or other geomorphological changes can cause relative sea level rise (RSLR) to be greater or less than eustatic rise. Along the Atlantic Coast of the United States, for example, an estimated RSLR of 2-4 mm/yr^{-1} has been calculated for a period spanning the last 50 years. In contrast, some areas along the Louisiana coast are experiencing a RSLR of 10 mm/yr^{-1}.

Changes in sea level affect all coastal ecosystems. Changes in hydrology will result as the duration and extent of flooding increases. How well mangrove ecosystems will adapt to this hydrological change will depend on the magnitude of the change and the ability of mangroves to either 1) increase mangrove sediment elevation through vertical accretion, or 2) migrate in a landward direction. The mangrove sediment surface itself is in dynamic equilibrium with sea level, since a local loss of elevation will result in faster sediment accumulation. The problem with accelerated sea level rise is that the rate of rise might be faster than the ability of mangrove forests to accumulate and stabilize sediments. Mangroves can migrate back into previous uplands, but only if there is enough space to accommodate the mangroves at the new intertidal level. Local elevation gradients may make this regression impossible.

Mangroves colonizing macrotidal environments and receiving land-based and/or marine sediments (i.e., riverine mangroves) are generally less vulnerable to changes in sea level rise than are mangroves in microtidal environments, such as in Florida and the Yucatan, or mangroves with restricted hydrology. Land-based and marine sediments increase vertical accretion through direct deposition on mangrove soils. Nutrient and freshwater supply tend to enhance mangrove productivity, which contributes to vertical accretion through the production and deposition of organic matter and root growth. Mangroves under restricted hydrology depend mostly on in-situ organic matter production to attain vertical accretion. Different mangrove ecotypes will therefore have differing sensitivities to increases in RSLR.

Sedimentation

Even though mangroves colonize sedimentary environments, excessive sediment deposits can damage them. Moderate sedimentation is beneficial to mangroves as a source of nutrients and to keep up with predicted increases in eustatic sea level rise. When excessive, sudden sedimentation can reduce growth or even kill mangroves.

Complete burial of mangrove root structures (aerial roots, pneumatophores) interrupts gas exchange, killing root tissue and trees. For example, *Avicennia* trees will die after 10 cm of root burial (Ellison 1998). Seedlings are especially sensitive to excessive sedimentation. Under experimental conditions, *Rhizophora apiculata* seedlings had reduced growth and increased mortality after 8 cm of sediment burial (Terrados et al. 1997). Excessive sedimentation can result from natural phenomena such as river floods and hurricanes, but also from human alterations to the ecosystem. Road and dam construction, mining, and dredge spoil have buried and killed mangroves.

Mangrove Pollution

Human-caused pollution in mangrove ecosystems includes thermal pollution (hot-water outflows), heavy metals, agrochemicals, nutrient pollution (including sewage), and oil spills. Oil spill toxicity is discussed in detail in Chapter 2. Thermal pollution is not common in the tropics but, when present, reduces leaf area and causes chlorotic leaves, partial defoliation, and dwarfed seedlings. Seedlings are more sensitive than trees, showing 100% mortality with a water temperature rise between 7 and 9 ºC (Hogarth 1999).

Mining and industrial wastes are the main sources for heavy metal pollution (especially mercury, lead, cadmium, zinc, and copper). When heavy metals reach a mangrove environment, most are already bound onto suspended particulates (sediments) and in general do not represent an ecological threat. Although the accumulation of heavy metals in mangrove soils has not been studied in detail, they may decrease growth and respiration rates of mangroves, and will also negatively impact associated animals. Concentrations of mercury, cadmium, and zinc are toxic to invertebrate and fish larvae, and heavy metals cause physiological stress and affect crab reproduction.

Runoff from agricultural fields represents the main source of organic chemical contamination in mangrove ecosystems. Little is known about the effects of pesticides in mangroves and associated fauna, although chronic effects are likely. As with heavy metals, many of these compounds are absorbed onto sediment particles and degrade very slowly under anoxic conditions. Despite the possibility of burial, heavy metals and pesticides may bioaccumulate in animals that use mangroves (especially those closely associated with mangrove sediments), such as fish, shrimp, and mollusks.

Nutrient pollution in mangroves can have various effects. Sewage disposal under carefully managed conditions can enhance tree growth and productivity as a result of added nutrients, especially nitrogen and phosphorus (Twilley 1998). However, if the rate of disposal is greater than the uptake rate (a function of forest size and mangrove ecotype), excessively high nutrient concentrations will result. This causes excessive algal growth, which can obstruct mangrove pneumatophores and reduce oxygen exchange. Algal mats can also hinder growth of mangrove seedlings (Hogarth 1999).

Chlorosis/chlorotic – **abnormal condition characterized by the absence of green pigments in plants, causing yellowing of normally green leaves.**

Anoxic – **Without free oxygen. Aerobic metabolism (e.g., bacterial respiration) can consume dissolved free oxygen in water and soils, resulting in anoxic conditions that are detrimental to oxygen-breathing organisms. (p.19)**

Bioaccumulate – **Uptake of dissolved chemicals from water and uptake from ingested food and sediment residues. (p. 19)**

Anchialine ponds – **A rare Hawaiian ecosystem, consisting of pools with no surface connection to the ocean, but affected by tides. These pools have a characteristic water quality and support an assemblage of animals and plants, many of which are endangered.**

Excessive microbial activity accompanies high levels of nutrients, and depletes oxygen in the water, which is harmful for mangrove-associated aquatic fauna.

Development and Forest Clearing

Despite the ecological and economic importance of mangroves, deforestation has been widespread. Deforestation has mostly been related to firewood and timber harvesting, land reclamation for human establishment, agriculture, pasture, salt production, and mariculture. Tropical countries have sustainably harvested mangrove wood for generations, but increasing populations have led to unsustainable practices. Human activities have had varying degrees of impact: a residential project in Florida destroyed approximately 24% of mangrove cover (Twilley 1998). In Ecuador, the leading exporter of farm-raised shrimp, approximately 45-63% of mangrove habitat in the El Oro River has been lost due to mariculture pond construction (Twilley 1989).

Despite laws established for mangrove protection in many different countries, unregulated exploitation and deforestation continues. In the Philippines, approximately 60% of the original mangrove area has disappeared. In Thailand, 55% of the mangrove cover has been lost over about 25 years. Eventually, the overexploitation of mangrove forests will degrade and, ultimately, lose habitat, increase shoreline erosion, damage fisheries, and lose services derived from these ecosystems.

Invasive Species

Mangroves have been successfully introduced in several tropical islands where they did not occur naturally, and may thus be considered an invasive species. Hawaii is an example of such a case, where the proliferation of *Rhizophora mangle* has deteriorated habitat for some endemic waterbirds and has damaged sensitive archaeological sites. The proliferation of mangroves has also been linked to the premature infilling of a unique Hawaiian aquatic ecosystem called anchialine ponds. Despite providing useful environmental services (e.g., shoreline protection, organic matter production, and water quality), the mangroves may proliferate in these foreign environments and seriously impact the native flora and fauna. The cost of their removal has been reported to vary from $108,000 to $377,000 per hectare (Allen 1998).

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CHAPTER 2. Oil Toxicity

Key Points

- Mangroves are highly susceptible to oil exposure; oiling may kill them within a few weeks to several months.
- Lighter oils are more acutely toxic to mangroves than are heavier oils. Increased weathering generally lowers oil toxicity.
- Oil-impacted mangroves may suffer yellowed leaves, defoliation, and tree death. More subtle responses include branching of pneumatophores, germination failure, decreased canopy cover, increased rate of mutation, and increased sensitivity to other stresses.
- Response techniques that reduce oil contact with mangroves, such as chemical dispersants, reduce the resultant toxicity as well. Tradeoffs include potential increased toxicity to adjacent communities, and increased penetration of dispersed oil to mangrove sediments.
- The amount of oil reaching the mangroves and the length of time spilled oil remains near the mangroves are key variables in determining the severity of effect.
- Mangrove-associated invertebrates and plants recover more quickly from oiling than do the mangroves themselves, because of the longer time for mangroves to reach maturity.

Weathering – **Changes in the physical and chemical properties of oil due to natural processes, including evaporation, emulsification, dissolution, photo-oxidation, and biodegradation.**

Canopy – **topmost layer of leaves, twigs, and branches of forest trees or other woody plants.**

Sublethal effect – **An effect that does not directly cause death but does affect behavior, biochemical or physiological functions, or tissue integrity.**

Introduction

In many tropical regions, mangrove forests are the defining feature of the coastal environment. Mangrove habitats represent the interface between land and sea and, as such, are one of the principal places where spilled oil and associated impacts converge. The diversity and abundance of the biological communities associated with mangroves are evident with the first visit to a healthy mangrove stand.

Observations from many spill events around the world have shown that mangroves suffer both lethal and sublethal effects from oil exposure. Past experience has also taught us that such forests are particularly difficult to protect and clean up once a spill has occurred because they are physically intricate, relatively hard to access, and inhospitable to humans. Each of these considerations contributes to the overall assessment that mangrove forests are a habitat at risk from oil spills. In the rankings of coastal areas in NOAA's Environmental Sensitivity Indices, commonly used as a tool for spill contingency planning around the world, mangrove forests are ranked as the most sensitive of tropical habitats.

In this chapter we discuss the toxicity of oil to the broad class of trees called mangroves. In contrast to other habitats, tropical or otherwise, there is a fairly robust literature on the effects of oil to mangroves. This work includes monitoring of mangrove areas oiled during actual spills, field studies of oil impacts on mangroves, and laboratory studies that attempt to control some of the variables that may otherwise complicate the interpretation of research results. Predictably, the body of results is not unanimous in type of impact or the severity of those documented, but there are some consistencies that can serve as the starting point for spill response guidance.

Mechanisms of Oil Toxicity to Mangroves

It is clear from spills, and field and laboratory studies, that—at least in many circumstances—oil harms or kills mangroves. What is less obvious is *how* that harm occurs and the mechanism of toxicity. Although there is some consensus that oil causes physical suffocation and toxicological/physiological impacts, researchers disagree as to the relative contributions of each mechanism, which may vary with type of oil and time since the spill (Proffitt et al. 1997).

One of the universal challenges faced by resource managers and spill responders when dealing with oil impacts is the fact that "oil" is a complex mixture of many kinds of chemicals. The oil spilled in one incident is almost certainly different from that spilled in another. In addition, oils within broad categories like "crude oil" or "diesel" can be vastly different, depending on the geological source of the original material, refining processes, and additives incorporated for transportation in barges or tankers. Even if we could somehow stipulate that all spilled oil was to be of a single fixed chemical formulation, petroleum products released into the environment are subjected to differential processes of weathering that immediately begin altering its original physical and chemical characteristics. As a result, samples of oil from exactly the same source can be very different in composition after being subjected to a differing mix of environmental influences.

Much like "oil," the term "mangrove" is also a broadly encompassing and sometimes vague category that defies strict definition (see Chapter 1). Mangroves are designed for life on the margin—literally. Because the generic term brings together many plant groups, it is easy to imagine the difficulties in forming generalities about the effects of any contaminant—much less an amorphous one like "oil." Nevertheless, we will try to do so.

Similar to the oil toxicity situation for many other intertidal environments, the mangrove-related biological resources at risk in a spill situation can be affected in at least two principal ways: first, from physical effects; second, the true toxicological effects of the petroleum.

Many oil products are highly viscous. In particular, crude oils and heavy fuel oils can be deposited on shorelines and shoreline resources in thick, sticky layers that may either disrupt or completely prevent normal biological processes of exchange with the environment. Even if a petroleum product is not especially toxic in its own right, when oil physically covers plants and animals, they may die from suffocation, starvation, or other physical interference with normal physiological function.

Mangroves have developed a complex series of physiological mechanisms to enable them to survive in a low-oxygen, high-salinity world. A major point to remember in terms of physical effects of oil spills on mangroves is that many, if not most, of these adaptations depend on unimpeded exchange with either water or air. Pneumatophores and their lenticels tend to be located in the same portions of the intertidal most heavily impacted by stranded oil. While coatings of oil can also interfere with salt exchange, the leaves and submerged roots of the mangrove responsible for mediation of salts are often located away from the tidally influenced (and most likely to be oiled) portions of the plant.

These physical impacts of oil are linked to adaptive physiology of the mangrove plants, but are independent of any inherent chemical toxicity in the oil itself. The additional impact from acute or chronic toxicity of the oil would exacerbate the influence of physical smothering. Although many studies and reviews of mangroves and oil indicate that physical mechanisms are the primary means by which oil adversely affects mangroves, other reviewers and mangrove experts discount this weighting. See, for example, Snedaker et al. (1997). They suggest that at least some species can tolerate or accommodate exposure to moderate amounts of oil on breathing roots.

The lighter, or lower molecular weight, aromatic hydrocarbons that often are major components of oil mixtures are also known to damage the cellular membranes in subsurface roots; this, in turn, could impair salt exclusion in those mangroves that have the root filters described in Chapter 1- adaptations to salinity. Disruption of ion transport mechanisms in mangrove roots, as indicated by sodium to potassium ion ratios in leaves, was identified as the cause of oil-induced stress to mangroves in the 1973 *Zoe Colocotronis* spill in Puerto Rico (Page et al. 1985). Mangroves oiled by the 1991 Gulf War spill in Saudi Arabia showed tissue death on pneumatophores and a response by the plants in which new, branched pneumatophores grew from lenticels—an apparently compensatory mechanism to provide gaseous exchange (Böer 1993).

Genetic damage is a more subtle effect of oil exposure, but can cause significant impact at the population level. For example, researchers have linked the presence of polynuclear aromatic hydrocarbons (PAHs) in soil to an increased incidence of a mangrove mutation in which chlorophyll is deficient or absent (mangroves such as *Rhizophora mangle* are viviparous and can self-fertilize, so they are well-suited for genetic screening studies such as those examining the frequency of mutations under different conditions; Klekowski et al. 1994a, 1994b). The presence or absence of pigmentation allows for easy visual recognition of genotype in the trees. The correlation between sediment PAH concentration and frequency of mutation was a strong one, raising the possibility that a spill can impact the genetic mix of exposed mangroves.

PAH – polynuclear aromatic hydrocarbon; also called polycyclic aromatic hydrocarbon, a component of oil. PAHs are associated with demonstrated toxic effects.

Genotype – Genetic makeup of an individual organism.

Infrared photography – **Photography using films sensitive to both visible light and infrared radiation. Live vegetation is particularly highlighted with infrared films and so is a useful tool for aerial surveys of live and dead plants.**

Acute Effects

The acute toxicity of oil to mangroves has been clearly shown in laboratory and field experiments, as well as observed after actual spills. Seedlings and saplings, in particular, are susceptible to oil exposure: in field studies with *Avicennia marina*, greater than 96% of seedlings exposed to a weathered crude oil died, compared to no deaths among the unoiled controls (Grant et al. 1993). Other studies found that mangrove seedlings could survive in oiled sediments up to the point where food reserves stored in propagules were exhausted, whereupon the plants died.

The *Avicennia* study cited above also found that fresh crude oil was more toxic than weathered crude. Based on laboratory and field oiling experiments conducted in Australia, the authors cautioned against readily extrapolating results from the laboratory to what could be expected during an actual spill. Container size and adherence of oil to container walls were thought to be important factors that may have skewed laboratory toxicity results by lowering actual exposure concentrations (Grant et al. 1993).

Another set of Australian studies investigated the toxicity of two oil types, a light crude and a Bunker C, to mature mangroves (*Rhizophora stylosa*) over a period of two years (Duke et al. 2000). A number of interesting results were obtained from this study, including:

- Unoiled control mortality was low over the two-year study period;
- Plots oiled with Bunker C showed no difference in mangrove mortality relative to unoiled controls;
- Mangroves treated with the light crude oil showed a significantly higher mortality than controls and the Bunker C treatment;
- Addition of chemical dispersant to the crude significantly reduced the toxicity but not to control levels;
- Most tree deaths occurred in the first six months after treatment.

The last observation is consistent with conditions observed at several oil spills in mangrove areas. In fact, obvious signs of mangrove stress often begin occurring within the first two weeks of a spill event, and these can range from chlorosis to defoliation to tree death. In the 1999 Roosevelt Roads Naval Air Station (Puerto Rico) spill of JP-5 jet fuel, an initial damage assessment survey conducted in the first month post-spill determined that 46 percent of mangrove trees, saplings, and seedlings along a transect in the most impacted basin area were stressed (defined as showing yellowed, or chlorotic, leaf color). This compared to 0 percent along the unoiled reference transect (Geo-Marine, Inc. 2000). Figure 2.1 shows the most heavily impacted area about nine months after the initial release with many of the initially stressed trees dead. Color infrared, aerial photography taken at regular intervals through 19 months post-spill confirmed the visual observations. Analysis of the infrared photographs of the affected mangrove area shown in Figure 2.1 indicated that two weeks after the release, 82 percent of the total mangrove area was classified as "impacted" relative to pre-spill conditions.

Under more controlled conditions, studies using fresh crude oils have suggested that defoliation, when it occurs, should reach a maximum between 4-12 weeks post-spill.

A monitoring study conducted in Australia after the *Era* spill in 1992 found a consistent set of mangrove responses including leaf staining, chlorosis, leaf death, and complete defoliation. Within three months after the oil washed ashore, extensive defoliation of mangrove trees had begun and many appeared to be dead. The degree to which mangroves were damaged and the extent that they recovered from spill damage were correlated to extent of oiling (Wardrop et al. 1996).

In the 1986 Bahía las Minas (Panama) spill, scientists monitoring the effects of the oil on mangroves recorded a band of dead and dying trees where oil had washed ashore five months previously. A year and a half after the spill, dead mangroves were found along 27 km of the coast. Photographs taken just before the spill showed no evidence of tree mortality (Jackson et al. 1989).

Figure 2.1 Aerial view of Roosevelt Roads, Puerto Rico jet fuel spill in 1999 showing dead mangroves (Dan L. Wilkinson, Geo-Marine, Inc).

Chronic Effects

The line between acute and chronic impacts can be a little blurry at times. In the case of mangroves, visible response to oiling may be almost immediate, with leaves curling or yellowing, as at the *Era* and Bahía las Minas spills. The tree, however, may survive for a time only to succumb weeks or months later. Alternatively, depending on the nature of exposure, it may recover to produce new leaf growth.

At least one researcher has summarized acute and chronic effects of oil to mangroves in tabular form, reproduced below (Lewis 1983). In this case, the line between acute and chronic effect was defined at 30 days; others may shift the border one way or the other.

Table 2.1. Generalized responses of mangrove forests to oil spills. From Lewis (1983).

STAGE	OBSERVED IMPACT
Acute	
0 - 15 days	**Deaths of birds, fish, invertebrates**
15 - 30 days	**Defoliation and death of small (<1 m) mangroves**
	Loss of aerial root community
Chronic	
30 days - 1 year	**Defoliation and death of medium (<3 m) mangroves**
	Tissue damage to aerial roots
1 year – 5 years	**Death of larger (>3 m) mangroves**
	Loss of aerial roots
	Regrowth of roots (sometimes deformed)
	Recolonization of oiled areas by new seedlings
1 year – 10 years?	**Reduction in litter fall**
	Reduced reproduction
	Reduced seedling survival
	Death or reduced growth of recolonizing trees?
	Increased insect damage?
10 – 50 years?	**Complete recovery**

Mangroves can be chronically impacted by oil in several ways. Stressed mangroves could show differences in growth rates or alter reproductive timing or strategy. They may also develop morphological adaptations to help them survive either the physical or chemical consequences of residual oil contamination. Such modifications may require expending additional energy, which in turn, could reduce the mangroves' ability to withstand other non-spill-related stresses they may encounter.

Figure 2.2 Close up of oil in mangroves with dead bird (C.E. Proffitt).

One consequence of the complex physical structure and habitat created by mangrove trees is that oil spilled into the environment is very difficult to clean up. The challenge and cost of doing so, and the remote locations of many mangrove forests, often results in unrecovered oil in mangrove areas affected by spills. This, in turn, may expose the trees and other components of the mangrove community to chronic releases of petroleum as the oil slowly leaches from the substrate, particularly where organic-rich soils are heavily oiled.

Researchers who have compared oil spill impacts at several different spill sites have found similar types of impacts that differ primarily in the magnitude of effect. The degree of impact appears to be related to the physical factors that control oil persistence on the shoreline and exposure to waves and currents. Interestingly, the presence and density of burrowing animals like crabs also affects the persistence of oil in mangrove areas and can determine whether an exposure is short- or long-term, because of oil penetration via the burrows into an otherwise impermeable sediment.

In many parts of the world, mangrove stands co-occur with industrial facilities and thus may be subjected to chronic contamination from petroleum compounds, other organic chemicals, and heavy metals. As a result, it can be difficult to determine the additional stress imposed by a spill event vs. existing stress. Newer assessment tools, such as molecular biomarkers, can isolate sources of stress more readily than non-specific but commonly used methodologies, and show promise for distinguishing spill impacts from other pollution sources.

- Follow-up studies of mangroves oiled during the 1991 Gulf War spill indicated that oiled pneumatophores that survived tended to develop branched secondary pneumatophores. These were observed two years after the spill in areas that were known to have been oiled, and were interpreted to be a response to impairment of normal respiration (Böer 1993)
- Studies of the 1986 Bahía las Minas (Galeta) oil spill in Panama concluded that its impact was "catastrophic." Five years after the incident, researchers suggested that oil remaining in mangrove sediments adversely affected root survival, canopy condition, and growth rates of mangrove seedlings in oil-deforested gaps. Six years after the spill, surviving forests fringing deforested areas showed continued deterioration of canopy leaf biomass (Burns et al. 1993).
- The follow-up study of the 1992 Era spill in Australia also noted a lack of recovery four years after the initial release—although effects themselves had appeared to have peaked, no strong signs of recovery were recorded in the affected mangrove areas (Wardrop et al. 1996).
- The experimental (i.e., intentional and controlled) 1984 TROPICS spill in Panama confirmed long-term impacts to oiled mangroves, termed "devastating" by the original researchers who returned to the study sites ten years later. They found a total mortality of nearly half of the affected trees and a significant subsidence of the underlying sediment. This was compared to a 17-percent mortality at seven months post-oiling, a level that appeared to be stable after 20 months (Dodge et al. 1995).

These results from the more intensively studied spills that have occurred in the last fifteen years suggest that chronic effects of such events can be measured over long time periods, potentially a decade or decades. They also indicate the difficulties in measuring longer-term impacts due to the time frames involved—and, hence, the value of longer-term monitoring of mangrove status following an oil spill.

Endpoint – A measured response of a natural resource to exposure to a contaminant, such as oil, in the field or laboratory.

Mangrove Community Impacts

With the realization that mangrove stands provide key habitat and nursery areas for many plants and animals in the tropical coastal environment, many researchers have included the associated biological communities in their assessments of oil impacts. Of course, this considerably broadens the scope of spill-related studies, but realistically, it would be arbitrary and artificial to consider only the impacts of oil on the mangroves themselves.

Studies of the Bahía las Minas spill in Panama concluded that significant long-term impacts occurred to mangrove communities. Both the habitat itself and the epibiotic community changed in oiled areas. After five years, the length of shoreline fringed by mangroves had decreased in oiled areas relative to unoiled areas, and this translated to a decrease in available surface area ranging from 33 to 74 percent, depending on habitat type. In addition, defoliation increased the amount of light reaching the lower portions of the mangrove forest (Burns et al. 1993).

In the Bahía las Minas spill, a massive die-off of plants and animals attached to the mangrove roots followed the initial release. Five years after the spill, the cover of epibiotic bivalves was reduced in oiled areas relative to unoiled reference areas. Open-coast study sites recovered more quickly, although differences in cover of sessile invertebrates remained significant through four years.

More controlled experimental oiling experiments have been less conclusive. One such study in New South Wales, Australia found that invertebrate populations were highly variable with differences attributable to oiling treatment difficult to discern. Though snails were less dense shortly after oiling treatments, they recovered by the end of the study period several months later (McGuinness 1990).

Another experiment in Australia focused on the effect of one toxic component of oil, naphthalene, on a gastropod snail common in the mangroves of eastern Australia. The sublethal endpoint used for impact assessment was the crawling rate of the snails. Two responses were elicited in short- and long-term exposures to naphthalene. An increased level of activity in the short-term exposure was interpreted as an avoidance response, while the decreased crawling rate induced by the longer-term exposure suggested a physiological consequence of the toxicant. The measurable differences in response attributed to the hydrocarbon implied that normal behavior patterns of the snails would be significantly disrupted by oil exposure (Mackey and Hodgkinson 1996).

The TROPICS experimental spill follow-up found no short- or long-term effects to three species of mangrove oysters studied in the experiment. In fact, populations at oiled sites showed the most substantial increases over time that was speculatively attributed to breakdown and mobilization of petroleum hydrocarbons as additional food sources (Dodge et al. 1995).

One area of focus in interpreting mangrove community impacts in the context of oil spill response has been comparing the toxicity of undispersed and dispersed oil to the mangroves themselves and to the associated invertebrate community. The limited findings are somewhat equivocal: one study found that dispersing oil appears to reduce the inherent toxicity of the oil to mangroves, but increases the impacts to exposed invertebrates (Lai 1986). Another assessment concluded no difference in toxicity to crustaceans from dispersed and undispersed crude oil (Duke et al. 2000). However, the same study also evaluated toxicity of Bunker C fuel oil and found that the crude oil was significantly more acutely toxic than the Bunker. The authors attributed this to the physical and chemical differences between the oil types.

The TROPICS study in Panama found a notable lack of mortality to mangrove trees at the oil/dispersant-treated site, in contrast to a measurable and seemingly increasing mortality at the oil-only treatment site.

Australian researchers studying the effects of the 1992 *Era* spill on fish populations around oiled mangroves found no measurable assemblage differences between groups inside and outside oiled zones, although juveniles of several species were significantly smaller in oiled creeks than in unoiled creeks (Connolly and Jones 1996).

Indirect Impacts

As is the case with most, if not all, spill-affected resources, some indirect impacts on mangroves have been identified. For example, residual oil remaining on the surface of mangrove sediments oiled during the Gulf War spill in Saudi Arabia increased the ambient soil temperatures to the point where germination and growth of intertidal plants was adversely affected (Böer 1993).

In Panama, the breakdown of protective structure provided by roots of dead mangroves caused a secondary impact from the oil spill at Bahía las Minas. For five years post-spill, the tree remnants had protected young seedlings, but when the roots finally gave way, drift logs crushed the recovering mangrove stand and essentially destroyed that part of the mangrove fringe (Duke et al. 1993).

Decomposition of the mangrove root mass following large-scale mortality causes significant erosion and even subsidence of the land where the forest was located. In the experimental TROPICS oiling, approximately 8 cm of surface elevation loss was noted by researchers who returned to the study site 10 years after the oiling (Dodge et al. 1995).

Prolonged flooding of diked mangrove areas due to cleanup operations is a possible indirect spill impact that would be limited to those areas where hydrologic conditions are easily controlled. This was suggested as a factor in the 1999 jet fuel spill at Naval Station Roosevelt Roads in Puerto Rico. In that spill, culverts providing water exchange with coastal waters were closed both to facilitate oil recovery and to prevent the spread of oil to other areas. However, in doing so, the water levels in some basin mangrove forests were held at much higher levels (> 1 meter) than the norm for periods of more than a week. It has been suggested that this action either contributed to or was a major source of mortality to mangroves in the weeks that followed (Wilkinson et al. 2000).

Even though a sublethal exposure to oil may not kill a mangrove stand outright, several post-spill, follow-up studies have suggested that oil can significantly weaken mangroves to the point where they may succumb to other natural stresses they ordinarily would survive. Examples of these stresses include cold weather and hypersalinity (Snedaker et al. 1997).

Summary and Response Implications

The body of literature available for the toxicity of oil to mangroves presents a range of results from which we can extract some points for spill response guidance.

- Mangroves are highly susceptible to oil exposure. Acute effects of oil (mortality) occur within six months of exposure and usually within a much shorter time frame (a few weeks). Commonly observed mangrove responses to oil include yellowing of leaves, defoliation, and tree death. More subtle responses include branching of pneumatophores, germination failure, decreased canopy cover, increased rate of mutation, and increased sensitivity to other stresses.
- Different oil types confer different toxicity effects. While this is a universal truth in spill response, for mangroves the lighter oils are more acutely toxic than heavier oils (for example, light crude oil is more toxic than a Bunker-type fuel oil). Similarly, less-weathered oil is more toxic to mangroves than the same oil that has been subjected to longer or more intense weathering.
- The physical effects of oiling (e.g., covering or blocking of specialized tissues for respiration or salt management) can be as damaging to mangroves as the inherent toxicity of the oil. Although some studies indicate that mangroves can tolerate some coating without apparent damage, many others identify physical effects of oiling as the most serious.
- Response techniques that reduce oil contact with mangroves reduce the resultant toxicity as well. For example, chemical dispersants seem to reduce oil toxicity to mangroves. In this case, the tradeoff is the possibility of increased toxicity to adjacent and associated communities, such as offshore coral reefs, and increased penetration of dispersed oil that may reach mangrove sediments.
- Comparing spill impacts at several mangrove sites indicates that variable effects are related to geomorphology and hydrologic kinetics of the mangrove ecosystem that, in turn, control whether oil persists in the mangrove habitat. Oiled mangrove forests that are sheltered from wave and current exposure are likely to be more severely affected than well-exposed, "outer fringe" mangrove areas. A physico-biological

consideration that also can be significant is the density of burrows from associated organisms such as crabs, which can increase the penetration and persistence of oil with depth into sediments. Berms can protect inner areas or concentrate oil in front of them.

- Mangrove communities are complex and, as might be expected, the impacts of oil to the associated plants and animals vary. The available information suggests that, while oil spills undoubtedly affect such communities, they appear to recover more quickly than the mangroves themselves. Because of this, longer-term effects are likely to be related to death of the mangroves and loss of the habitat that supports and protects the community.

As we have noted, the toxicity implications from an oil spill in a mangrove area depend on a wide variety of different factors. Generally, the amount of oil reaching the mangroves and the length of time spilled oil remains near the mangroves are key variables in determining the severity of effect. Although it is stating the obvious to a spill responder that prevention is the best tool for minimizing the environmental impacts of an incident, for mangroves this is especially true. Reducing the amount of oil reaching the mangroves not only reduces the short- and long-term toxicological effects but also reduces cleanup impacts and the potential for chronic contamination. In a response, these considerations may translate into increased protection for mangroves at risk from exposure and possible use of response measures that reduce that exposure (e.g., open-water countermeasures such as burning or dispersants, shoreline countermeasures such as chemical cleaners or flushing). The long-term character of many of the mangrove impacts that have been observed argues for serious consideration of such strategies.

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Biogenic – **In mangroves, the trees themselves create the habitat. Biogenic also means "resulting from the actions of living organisms."**

CHAPTER 3. Response

Key Points

- Mangroves are highly sensitive to oil and often are priority areas for protection.
- Winds and tides carry spilled oil into mangrove forests, where oil coats the soil surface, aerial roots, and propagules.
- Dispersing or burning oil offshore can prevent or lessen impacts to mangroves.
- Spill containment and cleanup techniques should minimize any additional impacts to mangroves and other natural resources at risk.

As detailed in the previous chapter, mangroves are particularly sensitive to oil and, where they are native, often are priority areas for protection. The objective of spill response in mangroves, as in any habitat, is to minimize the damage caused by the accident and released oil. Spill containment and cleanup techniques should minimize any additional impacts to mangroves. Mangrove forests are a biogenically structured habitat—the trees themselves create the habitat. Death of the trees, the structuring organism, causes loss of habitat, with corresponding impact on the suite of associated species dependent upon them, including offshore resources such as coral reefs. Potential response strategies should be evaluated to determine whether the ultimate benefits from the response action outweigh any environmental costs to the mangrove forests and associated sensitive habitats at risk.

Variables such as oil type, weather, location, and availability of response equipment will determine initial spill response options. In the best-case scenario, oil is prevented from moving into and contaminating mangrove areas. Promising, on-water response techniques that can help prevent oil from reaching mangrove forests include chemical dispersion and in-situ burning.

On-Water Response Options to Prevent Mangrove Oiling

Mechanical Recovery Offshore

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 very large spills offshore. Weather and sea conditions, the nature of the oil, and other factors may limit the effectiveness of mechanical recovery. In such cases, alternative open-water response techniques, such as dispersant application or in-situ burning of oil on water, may significantly reduce the risk that oil will reach shore and impact mangroves and other sensitive intertidal and shoreline habitats.

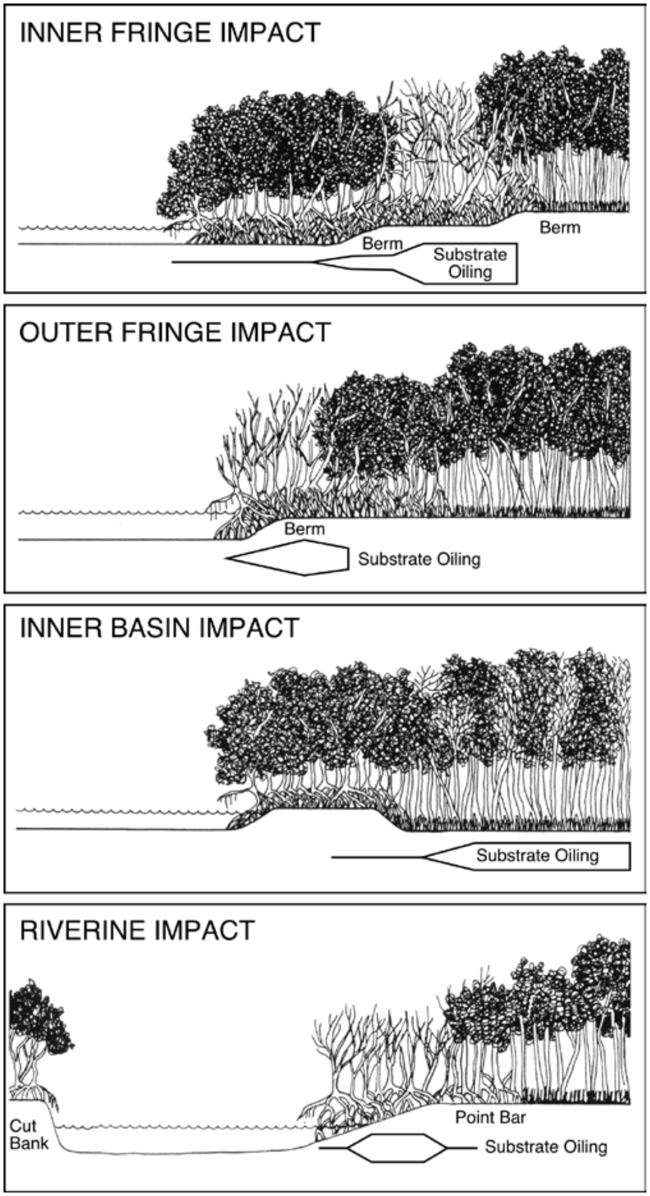

Figure 3.1 Schematic showing possible impacts to different types of mangrove forests from oiling (Research Planning Inc.).

Offshore Dispersant Application

Chemical dispersants are products applied to oil on the water surface to enhance formation of fine oil droplets, which mix into the water column and are dispersed by currents. Most oils physically disperse naturally 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 and marine mammals) and reduces the amount of floating oil that reaches sensitive nearshore and shoreline habitats. If applied appropriately offshore, chemical dispersants can be an effective tool for protecting mangrove forests 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 coral reefs, should be considered before dispersant use. When applied appropriately in sufficiently deep water, impacts to corals are expected to be minimal.

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 can remove large quantities of oil quickly and efficiently with minimal logistical support. Like dispersants, in-situ burning can help minimize impacts to wildlife at the water surface and reduce the amount of oil that reaches sensitive nearshore and shoreline habitats, including mangroves. 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 mangroves.

Wrack – Organic material, usually from dead seagrass or algae that wash up on shorelines.

It is important to note that, in contrast to open-water burning, in-situ burning should **not** be conducted within mangrove forests, as explained below under "Response Techniques Inappropriate for Mangroves."

Oil Behavior in Mangroves

Mangroves grow in low-energy depositional areas, which also tend to be the sites where oil accumulates (Figure 3.1). Spilled oil is carried into mangrove forests by winds and tidal currents. Oil slicks generally move into mangrove forests when the tide is high, depositing on the soil surface and on aerial roots and propagules when the tide recedes. The resulting distribution of deposited oil is typically patchy due to the variability in tidal heights within the forest. If there is a berm or shoreline, oil tends to concentrate and penetrate into the berm or accumulated detrital wrack. The oil can penetrate into the soil, particularly through crustacean burrows and other voids like those formed by dead mangrove roots. Lighter oils tend to penetrate more deeply into mangrove forests than heavier and more weathered oils, but will not persist unless they mix into the soil. However, crude oils and heavier refined products can pool onto sediment surfaces and are highly persistent. These heavy oils and emulsified oil can be trapped in thickets of red mangrove prop roots and black mangrove pneumatophores and are likely to adhere to and coat these surfaces, as well as other organic materials, such as seagrass wrack. Re-oiling from resuspended oil, particularly as tides rise and fall, may further injure plants over time. Where oil persists, sheens may be generated for months or years (Figure 3.2).

Assessing the extent and distribution of stranded oil can be difficult, particularly in dense forests, because the forest interior sometimes can be oiled even if the mangrove fringe is not, due to its lower tidal height. Access to interior areas of forests usually must be limited in order to minimize damage. Also, the tree canopy may hide oil on the ground during oil-observation overflights. Affected areas may become more apparent from the air as trees die or defoliate. Oiled trees may start to show evidence of effects, such as leaf-yellowing, within weeks after oiling. Trees may take months to die, especially with heavy oils.

Figure 3.2 Oil stranded in and around mangrove islets in Tampa Bay (Bouchard Barge B-155 spill, 1993; NOAA OR&R).

Cleanup of oiled interior mangroves can be particularly difficult because some mangrove forests are nearly impenetrable. Intrusive cleanup operations may significantly damage roots and seedlings, and also trample oil deeper into sediments, where it is slower to break down. Consequently, access to interior areas of mangrove forests should be limited and highly supervised. During later, less-supervised stages of mangrove cleanup on Eleanor Island at the 1993 *Bouchard B-155* Bunker oil spill in Tampa, Florida, cleanup workers reportedly spread oil from the mangrove fringe to the roots of previously unoiled mangrove plants in the mangrove interior as they moved back and forth removing surface sediment contamination. In spills of relatively fresh, lighter oil, such as diesel or crude, sediment penetration and toxic damage can occur very rapidly and the oil can break down relatively quickly. In such cases, cleanup operations are not expected to save many mangrove trees or effectively remove much oil, and any benefits are probably outweighed by the potential additional damage from access for cleanup.

Anaerobic – Occurring with little or no oxygen.

Natural processes will eventually remove remaining oil. Tidal action and precipitation can help physically flush stranded oil out of contaminated mangrove areas. Weathering processes degrade the oil, gradually reducing quantity and toxicity. Oiled substrate may not be able to support mangrove growth while toxicity levels remain high. Oil can degrade quickly in warm tropical environments, but more slowly if degradation is inhibited by anaerobic soil conditions. Oil may persist for very long periods in the peaty or muddy sediment where mangroves are most often found. Heavier oils can persist in mangrove sediment for decades after a spill.

Cleanup Options for Oiled Mangroves

If mangrove forest shorelines are oiled, extreme caution must be exercised in selecting cleanup activities. Potential benefits of oil removal must be weighed against the risks of potential additional harmful impacts from the cleanup technique.

No Action/Natural Recovery

There are several circumstances under which it is appropriate to do nothing. The foremost of these situations is when cleanup would cause more harm than benefit to mangroves or other associated habitats, or when shorelines are inaccessible. When no cleanup is conducted, oil will slowly degrade and be removed naturally, assisted by natural and storm-generated flushing. (See *Era* spill case study, Chapter 5.)

Spills of light oils, which will naturally evaporate and break down very rapidly, do not require cleanup. Such light oils are usually gone within days. Furthermore, light fuel oils such as gasoline and jet fuels typically impart their toxic impacts immediately, and cleanup can do little to reduce the damage. The only light refined product that might warrant some cleanup is diesel (No. 2 fuel oil) if sediment could be contaminated. It is important to recognize, though, that even where no cleanup is advisable, light oils can cause significant injury and contaminated mangrove habitats may require many years to recover.

Cleanup also is not recommended for small accumulations of oil, regardless of product type. Impacts caused by light accumulations generally do not warrant the tradeoffs associated with cleanup activity. Even for major spills, there may be cases for which it is best to take no action, depending on the nature of the oiling and the characteristics of the mangrove forest affected. Generally, cleanup should not be conducted in interior areas of mangrove forests because of the risk of damaging mangrove roots and seedlings, trampling oil into the sediment where it will degrade much more slowly, and spreading oil into previously unoiled areas. Exceptions may be made if access is possible from upland areas or if vegetation is sparse enough to permit access without injury to pneumatophores and prop roots. If cleanup is attempted in interior mangroves, experienced personnel must constantly oversee cleanup crews to prevent further injury.

In any case, attempts should be made to control the movement and spread of any mobile oil within the mangroves to prevent contamination of adjacent areas. Several response techniques described below, including barriers, passive collection, and flushing can be used to help control and contain mobile oil.

Barrier Methods

Several forms of barriers can deflect or contain oil, including booms, sediment berms, dams, and filter fences. Barriers can be used along mangrove shorelines and inlets to prevent oil entry. Proper strategic boom deployment in sheltered lagoon areas may be highly effective in trapping large quantities of mobile oil and reducing oil impact to interior mangroves. To be effective, barriers must be deployed immediately after a spill before oil moves into mangrove areas. This means that appropriate types and sufficient amounts of barrier materials must be stockpiled and available at the time of the spill, and that strategies for boom placement and deployment have already been established and tested.

Because of the soft substrate and sensitivity of prop roots and pneumatophores, barrier methods should be deployed carefully and maintained vigilantly to prevent physical damage during installation and removal. Untended boom that breaks loose can become entangled in the mangrove fringe, breaking off pneumatophores, prop roots, and juvenile plants. Boom deployed under inappropriate conditions or improperly deployed can cause additional harm, so caution must be exercised in planning where, when, and how boom will be used.

There are some shorelines where barriers will be ineffective due to physical characteristics, such as current strength and water depth. Where barrier methods are not an option, mangrove forests will remain vulnerable to contamination. For example, booms generally cannot be deployed successfully along mangrove shorelines with strong currents or along sections of mangrove shorelines behind shallow flats. Also, boom usually is not effective with light oils because they can readily mix into the water column and pass under floating boom. Heavier oils are more likely to remain at the water surface and so are more easily controlled with booms, although very heavy oils can sometimes become negatively buoyant and pass under boom.

Manual Oil Removal

Manual removal, using hand tools and manual labor, is often conducted to remove bulk oiling by heavier oils, such as crude oil or Bunker C oil, stranded in mangroves. Manual removal can help prevent other areas from becoming contaminated as the oil moves around, and helps limit long-term sediment contamination. Consideration should be given, however, to the trade-off between these benefits of manual removal and the mechanical damage to the mangroves that often accompanies manual cleanup. It is nearly impossible to reach the tangle of prop roots and pneumatophores of most mangroves without causing physical damage. Trampling of oil deeper into the sediment from foot traffic can be another harmful consequence of manual cleanup. Garrity and Levings (1996) observed that black mangrove pneumatophores along paths used by cleanup workers were significantly more likely to be killed than those in areas accessed by one or a few workers. Where pneumatophores had been dense at the time of the spill, paths often were bare substrate by 15 months post-spill as broken pneumatophores died and rotted away. (See Bahía las Minas case study.)

If manual removal is conducted in mangroves, and particularly in interior areas, consideration should be given to ways to minimize foot traffic and other impacts. Conducting activities from boats, when possible, is advisable. Close supervision of cleanup crews is essential.

Passive Collection with Sorbents

Sorbent boom or other sorbent materials can be placed at the fringe of oiled mangrove forests to passively recover any mobile oil, including sheens. Sorbents are oleophilic and either absorb or adsorb oil. They can be composed of either synthetic or natural materials, and they come in a variety of forms, including sausage boom, "pom-pom" or snare boom, sheets, rolls, pellets, and loose particulates. Sorbents vary in their effectiveness depending upon oil type, degree of oil weathering, and sorbent absorption or adsorption capacity. Sorbent materials must be placed and removed carefully to minimize disturbance of sediments and injury to mangrove roots. Sorbent materials must be closely monitored to ensure they do not move and damage mangrove roots, and must be removed when they become saturated or are no longer needed.

Sorbents have been used to wipe heavy oil coating from mangrove surfaces. Before using sorbents in this way, consideration should be given to associated physical damage. This activity is best conducted under close supervision and only in areas where substrate is firm enough to prevent oil mixing into it.

Vacuuming

Vacuuming can remove pooled oil or thick oil accumulations from the sediment surface, depressions, and channels. Vacuum equipment ranges from small units to large suction devices mounted on dredges, usually used outside vegetated areas. Generally, vacuuming should be conducted only at the outer fringe of mangrove forests; it is most feasible and least damaging where vegetation is not very dense, enabling easy access. Vacuuming can be used effectively on heavier and medium oils, providing they are still reasonably fluid. Lighter, more flammable petroleum products such as jet fuel and diesel generally should not be vacuumed.

As shown in Figure 3.3, vacuuming was used effectively to remove thick mats of Bunker C oil that stranded in mangroves during the 1993 Tampa Bay oil spill response (see Case Studies for more details). Vacuuming worked particularly well where oil stranded on sand substrate at the mangrove fringe. The technique was less effective over fine sediment and oyster beds. In order to minimize cleanup damage, care was taken to place the vacuum barge over firm sand substrate, where there were no seagrass beds.

Ambient Water Flooding (Deluge) and Low-Pressure Ambient Water Flushing

Low-pressure flushing with ambient seawater can wash fluid, loosely adhered oil from the sediment surface and mangrove vegetation into areas where it can be collected, as long as it can be done without resulting in significant physical disturbance of the sediment. Generally, flushing is most feasible at the outer fringe, but can sometimes be used to remove oil trapped within the mangrove forest. Flushing at water levels high enough to submerge sediments may help minimize impact to the substrate. If substrate mixing is likely or unavoidable, responders should allow the oil to weather naturally. Flushing is not effective with heavy oils, such as Bunker C, or highly weathered oils. Oil should be flushed only during ebbing tides to move it out where it can be collected.

Flushing can be a useful technique to help control the movement and spread of mobile oil in mangrove areas to prevent contamination of adjacent areas. When flushing free-floating oil, care should be taken to minimize emulsification.

Chemical Shoreline Cleaners

Chemical shoreline cleaners are products sprayed on oil-coated surfaces to "loosen" the oil so that it can be flushed off with ambient water. Tidal waters or water sprays alone cannot effectively wash away heavy oil. Shoreline cleaning products vary in their toxicity and recoverability of the treated, mobilized oil. Chemical shoreline cleaners loosen or dissolve heavy oil deposited over the lenticels on coated prop roots or pneumatophores so the residue can be washed away and lenticel functioning restored. Functioning of the lenticels, which enable delivery of oxygen to the subsurface roots, is critical to survival of the trees.

Some experimental studies (Teas et al. 1987, 1993) have reported promising results using chemical shoreline cleaners on mangrove trees coated with oil. A shoreline cleaner (Corexit 9580) applied to oiled red mangroves coated with Bunker C oil and then washed with seawater (within 7 days of oiling) reportedly effectively reduced oil adhesion and exposed the lenticels, restoring their air permeability. The study concluded that mangrove trees can be saved with shoreline cleaners if the interval between oiling and cleaning is no longer than about a week. Another study (Quilici et al. 1995) reported harmful effects on mangrove trees treated with shoreline cleaner without flushing. Results likely depend on the particular product used and application technique. Further testing and more experience with the effectiveness and effects of using shoreline cleaners on mangroves are needed to determine whether their use is advisable.

Figure 3.3 Cleanup worker removing heavy oil by vacuuming among mangrove prop roots in Tampa Bay during 1993 spill (NOAA OR&R).

Nutrient Addition/Bioremediation

Nutrient addition can enhance biodegradation of oil under nutrient-limited conditions. Microbes and essential nutrients for oil degradation generally are not limited in mangrove habitats, so nutrient enrichment may not offer much benefit. Studies conducted by Teas et al. (1991) and Quilici et al. (1995) concluded that adding fertilizer does not significantly enhance biodegradation of oil in mangrove sediment. Another study (Scherrer and Mille 1989) reported that oleophilic fertilizer enhanced the oil biodegradation process in peaty mangrove sediment, though the fertilizer in this experiment was added to the oil before the mangrove vegetation was contaminated. In any case, applied nutrients would be difficult to keep in place as tides flood through mangrove forests. There is also some risk that nutrient application might cause localized eutrophication and acute toxicity, particularly from ammonia, due to low mixing rates and shallow waters.

Burns et al. (1999) concluded that aeration of contaminated sediments may be effective in enhancing biodegradation of oil in mangrove sediments, since mangrove sediments are usually anaerobic below surface layers. The researchers suggest a bioremediation strategy that employs selective aeration to promote the survival of the trees vital to maintaining the structural integrity of the mangrove forest. The trees also provide the habitat necessary for the return of burrowing animals to impacted sediments. Burns et al. (1999) point out that aeration is not necessarily a strategy to be used over large areas. Reports on trial experiments to test this strategy are not yet available. More testing of this potential response technique is needed.

Removal of Oiled Wrack and Debris

Heavily oiled wrack and debris should be removed if it can be done without significantly damaging prop roots, pneumatophores, and seedlings or trampling oil into the sediment. However, oiled wrack should not be removed until the threat of oiling has passed, since wrack and leaf litter can act as a sort of natural barrier sorbent and actually protect the trees from direct oil contact. Unoiled and lightly oiled wrack and leaf litter should not be removed because they provide habitat and contribute to the ecosystem.

Table 3.1 Chart summarizing recommendations for various response techniques in oiled mangrove forests. (From Characteristic Coastal Habitats: Choosing Spill Response Alternatives, *NOAA OR&R 2000.)*

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

Oil Category Descriptions

I – Gasoline products
II – Diesel-like products and light crudes
III – Medium grade crudes and intermediate products
IV – Heavy crudes and residual products
V – Non-floating oil 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 Techniques Inappropriate for Mangroves

Under no circumstances should live mangrove vegetation be cut or burned. Both techniques will destroy trees and mangrove habitat. Mangrove trees are slow-growing and take decades to be replaced by mature vegetation. The loss of a large number of trees may compromise the forest structure, making it unlikely to recover naturally. Other cleanup techniques used at some oil spills but inappropriate in mangroves include mechanical oil removal, high-pressure or hot-water flushing, steam-cleaning, slurry sand blasting, trenching, and sediment reworking, tilling, or removal. All these methods would severely damage or destroy mangrove forests and associated organisms and habitats. Techniques such as pressure washing and sand blasting risk causing severe erosion.

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CHAPTER 4. Mangrove Recovery and Restoration

Key Points

- Mangroves can take more than 30 years to recover from severe oil spill impacts.
- Adequate tidal exchange is critical to restoration success.
- Mangrove seedling and tree density and health are the only widely measured recovery indicators at many spills.
- Restoration that works with natural recovery processes to reestablish mangrove habitat is the best course of action over the long term.

Mangrove ecosystems around the world suffer degradation from logging, coastal development, spraying of herbicides, conversion to fish ponds, and from oil spills and other pollutants. The continued loss of mangrove forests worldwide underscores the importance of projects focusing on restoration of forest structure and functions.

Since mangroves take 20–30+ years to recover from severe oil spill impacts, restoration projects attempt to speed up this recovery process. Adequate tidal exchange is most critical to restoration success. Mangrove restoration projects in Florida and the Caribbean often involve re-establishing natural hydrologic and tidal regimes, planting mangrove propagules, and/or planting marsh plants to provide a "nurse" habitat that can be colonized more easily than bare areas by mangrove trees.

An oil spill alone rarely changes the basic geophysical appearance and shape of the mangrove ecosystem; this is left for hurricanes, clear-cutting, and development. For this reason, restoration after an oil spill may be easier than after an event that substantially changed tidal elevation or hydrology or decimated mangrove trees. However, an oil spill may come as an additional impact on a mangrove ecosystem already degraded by human and industrial development, such as near refineries (Bahía las Minas), ports, or airfields (Roosevelt Roads). Cumulative or chronic impacts may decrease the resiliency of the mangrove ecosystem and increase the time it takes the system to recover or make it more difficult for the system to recover at all.

As with other marsh ecosystems adversely impacted by oil spills, we have learned valuable lessons from past mangrove restoration projects, including those that failed. Restoration projects need a clear goal from the outset that is based on understanding the mangrove ecosystem's natural ability to recover. The most effective role for restoration projects is to correct or assist when natural recruitment mechanisms are impeded or no longer functioning.

Recovery

Figure 4.1 Restoration project showing forestry technicians planting Rhizophora harrisonii *propagules in the Congal Biological Station, Esmeraldas Province, Ecuador (Arlo H. Hemphill).*

Mangal **– a mangrove forest and its associated microbes, fungi, plants, and animals.**

Recovery of any impacted ecosystem following a perturbation such as an oil spill is interpreted by many to mean a return to the system in place at the time of the spill. Mangroves' specialized niche is in a unique, changeable zone, subject to sediment flow that accretes and erodes, varying amounts of fresh water, impacts from storms and hurricanes, invasion by foreign species, and predation. Thus, even if we had a precise description of ecosystem conditions just before the spill, we still might not be able to return it to its pre-spill state.

A more practical way to measure recovery is to compare the impacted system with an unimpacted one (hopefully, nearby), using metrics such as tree height, density, canopy cover, above-ground biomass, and abundance and diversity of associated invertebrates, fish, and plants. Since compromised ecosystems can be more vulnerable to stresses such as disease or predation, the recovering habitat must also show the resilience of a functioning ecosystem.

Sadly, it is rare to find long-term, follow-up studies on mangroves beyond 1-2 years post-spill. It is even rarer to find studies that measure associated communities of invertebrates or other components of the mangal (mangrove forest habitat) besides the mangrove trees themselves. Even when mangrove *trees* appear to have recovered, restored mangal may differ from unimpacted mangal in its functioning and ecosystem complexity. Even with its limitations, mangrove tree density and health are the only widely measured recovery indicators at many spills, so we are using mangrove tree recovery to compare between spills shown in Table 4.1. Keep in mind that the recovery times indicated would probably be even longer if more comprehensive and ecological recovery measures were used.

Table 4.1 summarizes impacts and recovery times for mangrove trees at eight oil spills impacting five regions. Mangroves in the Bahía las Minas region of Panama were oiled by the *Witwater* spill in 1968 and again in 1986 by a refinery spill. Mangroves at Roosevelt Roads Naval Air Station in southeastern Puerto Rico were impacted by spills in 1986 and again in 1999, though different sections of mangroves were oiled at each spill. Because of the short duration of the follow-up studies, no cases were able to document recovery, except for fringe mangroves at the *Witwater* spill. In most of these studies, mangroves were regrowing in the oil-impacted areas but tree height, percent area of open canopy, and other parameters remained different from controls.

Da Silva et al. (1997) diagrammed generalized mangrove impact and recovery from an oil spill in four stages. These timeframes are approximate and will likely vary in different systems. See also Table 2.1 in Chapter 2 for additional details on timeframes for oil impacts to mangroves.

- Initial impact ~ 1 year
  propagules and young plants are most likely to die during this time
- Structural damage ~ 2 1/2 years
  trees begin to die
- Stabilization ~ 5 or more years
  deterioration of mangroves ceases, but no improvement noticeable
- Recovery ~ timeframe unknown
  system improves via colonization, increased density, etc.

Additional impacts such as from hurricanes, or other natural or human-caused disturbances could significantly delay these recovery processes.

Mangrove Restoration

Restoration success has rarely been studied quantitatively, but we know restored mangrove ecosystems often do not equate with natural ones. Shirley (1992) found that plant diversity was similar in restored and natural forests one year after restoration, but that environmental conditions were different and a number of fish and invertebrate species were absent from the restored site. McKee and Faulkner (2000) found that development of structure and biogeochemical functions differed in two restored mangrove stands because of different hydrological and soil conditions. Tree production and stand development was less where tidal exchange was restricted, and some waterlogging occurred due to uneven topography. Other assessments of restoration success, in terms of initial survival and percent cover after one or several years, have been mixed. Cintron (1992) reviewed a number of these projects.

These experiences emphasize the need for developing clear restoration goals that incorporate the mangrove ecosystem and its functions, as well as the growth and health of the trees themselves. Once the goal is defined, the project is designed and implemented, followed by monitoring to ensure that restoration is proceeding as anticipated. Projects should be monitored for 10 or more years to adequately assess long-term survival, resiliency, and complexity of the restored system (Field 1998). Depending on the type of impact and the state of the impacted mangal, restoration may take several approaches:

- Replant mangroves
- Remediate soils
- Encourage natural regeneration through improved site conditions
- Restore an alternate site to provide similar habitat (in-kind restoration)

Table 4.1. Impacts and recovery times for mangrove trees at eight oil spills impacting five regions.

Table 4.1. Impacts and recovery times for mangrove trees at eight oil spills impacting five regions.

Location	Oil type	Mangrove Impacts	Mangrove Recovery	Published reports
Era, Australia August 1992	Bunker fuel	*Avicennia marina* 75-100 ha impacted	> 4 yr.	Wardrop et al. 1997
Santa Augusta, US Virgin Islands 1971	Crude	*Rhizophora mangle*	>7 yr. (little to no recolonization)	Lewis 1979
Zoe Colocotronis, Puerto Rico March 1973	Venezuela crude	*Rhizophora mangle* *Avicinnia nitita*	>6 yr. (mangrove fringe)	Nadeau and Bergquist 1977, Gilfillan et al. 1981
Witwater, Panama, 1968		49 ha deforested	23 yr. (fringe) > 23 yr. (sheltered)	Duke et al. 1997
Bahía las Minas, Panama April 1986	Crude	*Rhizophora mangle* *Laguncularia racemosa* *Avicennia germinans* *Pelliciera rhizophorae*	>5 yr. (fringing mangroves) >6 yr. (recovery underway)	Garrity et al. 1994 Duke et al. 1997
Roosevelt Roads NAS, Puerto Rico Nov 1986 October 1999	Jet fuel (JP-5)	*Laguncularia racemosa* 6 ha killed (1986) 31 acres impacted (1999)	 > 1yr. > 1.5 yr.	 Ballou and Lewis 1989 Wilkinson et al. 2001
Tampa Bay, August 1993	No. 6 & No. 2 fuel	*Avicennia germinans* *Rhizophora mangle* *Laguncularia racemosa* 5.5 acres oiled	> 2 yr.	Levings et al.1995, 1997

Replant Mangroves

There is an extensive body of technical information on replanting mangroves. Specific details on elevation, use of fertilizer, planting density, species selection, etc. can be found in Snedaker and Biber (1996) and Field (1996, 1998). Today, restoration projects have moved away from broad use of planting except in those cases where natural processes are inadequate to naturally repopulate the area with recruits from surviving trees or more distant sources. Examples include mangrove forests where hydrology has been substantially altered, or where physical barriers such as dead trees, debris, or berms restrict circulation such that propagules have no access to denuded areas.

If planting is chosen as the best course, seedlings will survive best when they are planted in a sheltered location and at appropriate tidal elevation levels for each species. Planted seedlings are lost primarily because of erosion, predation, death from natural causes, planting at incorrect elevations, and residual oil toxicity (Getter et al. 1984). Planting one- to three-year old trees (usually supplied from nurseries) costs more but results in much better survival rates, especially in locations exposed to higher wave energy. Seed-

lings and propagules can survive even when planted in soils with residual oil contamination, though generally only after oil has weathered for 9-12 months.
Red mangrove seedlings (*R. mangle*) survived when planted in areas with one-year old residual oil at Bahía las Minas. A restoration planting project at St. Croix in the U.S. Virgin Islands planted seedlings 8 years after heavy oiling from the *Santa Augusta* spill, with 40% survival after two years (Lewis 1989).

Planting is still used to establish new mangrove forests in areas where they have not previously existed (such as in newly accreted shorelines or along human-built structures), or to replant in forests that have been logged. Survival of planted mangroves ranges from 0% to as high as 80% after one year. Lowest rates are often in areas with high wave energy where propagules are simply washed away. A planting technique that successfully increases survival rates of planted mangroves in exposed areas is called the Riley encasement method. Seedlings are planted inside PVC tubes (bamboo can also be used) to anchor and protect the seedlings until they become established (Rothenberger 1999).

Survival rates drop as the time after planting increases (e.g., one to two years or more). Even when plantings survive and grow, densities of planted trees may be lower than those naturally recruited, as found at the Bahía las Minas spill. Five years post-spill, replanted *R. mangle* survived well (especially in sheltered areas), but trees were less dense than in areas that recolonized naturally (Duke 1996). Restoration that enhances natural recovery processes to reestablish mangrove habitat has proven to be the best course of action over the long term.

Remediate Soils

Residual oil that has contaminated soils in mangrove forests degrades very slowly, since these soils are anaerobic below the top 1-2 mm (Burns et al. 2000). Experiments and field studies examining the possibility of accelerating oil degradation through addition of nutrients or increased aeration have shown little advantage to these methods. During the first year after a spill, biodegradation occurs at very low levels, and the main routes of oil removal are dissolution and evaporation. Thus, it is critical during spill response to attempt to keep oil from penetrating into sediments. Some restoration-planting projects surround seedlings with clean, fertilizer-augmented soil so the new trees can establish themselves and develop root structures in uncontaminated soils, before having to contend with possible toxic effects from residual oil.

Erosion of soils in mangrove forests following a disturbance can impede future re-establishment of new trees, since mangroves thrive only at specific tidal elevations. Since mangrove root mass comprises 40-60% of the total forest biomass, any substantial die-off of adult trees, as may occur after an oil spill, could cause subsidence of soils and erosion as a secondary impact. In such cases, augmenting soils, or assisting processes of sediment accretion may be a necessary part of restoration activities.

Encourage Natural Regeneration

Restore hydrology

Adequate hydrology is tagged as the most important parameter for mangrove recruitment (Lewis and Streever 2000). When tidal connections have been cut off or altered, as is common along developed coasts, re-establishing these connections can promote natural recruitment and improve the overall health and functioning of the mangrove ecosystem. Roosevelt Roads NAS is an example where impounded mangroves were impacted by a jet fuel spill in 1999. These mangroves suffered both from toxic fuel impacts and from extended submersion of roots when tidal conduits were closed to contain the spill during response. Facilitating or increasing tidal exchange to these impounded mangrove forests could be a promising restoration activity. In-kind restoration conducted after the Tampa Bay spill involved, in part, restoring tidal circulation at a previous dredge disposal site where mangroves had been impounded by dikes.

Plant "nurse" habitat

Since mangrove propagules and seedlings grow best in sheltered conditions, one strategy for more exposed areas is to plant indigenous marsh plants such as *Spartina alterniflora* to create a nurse habitat. These plants grow quickly (one to two years), trap and hold sediments (which decreases erosion), and create a more sheltered habitat where young mangroves can establish themselves. This staged approach is modeled after natural successional patterns and boosts natural recruitment of mangroves (Mauseth et al. 2001).

Propagules may be available only during certain times of the year or may not distribute far from the parent tree due to poor circulation or blocking by debris. Removing floating debris that may block channels enables propagules to reach and recolonize denuded areas naturally.

Restore in-kind resources

Increasingly, in-kind restoration is used for projects in the United States, especially for resource damage settlements after oil spills. In-kind restoration restores habitat in a different location in the same ecosystem and is meant to contribute to the overall habitat function of the region.

A recent example of in-kind restoration is Tampa Bay, Florida, where several mangrove islets were heavily oiled during a spill in 1993. Restoration efforts purchased a former dredge disposal site within Tampa Bay that included degraded mangrove forest. Tidal connections were restored, marsh grasses were planted along the shoreline, and the land was deeded to the County to function as wildlife habitat and provide water filtering functions for the waters of Tampa Bay (see Case Studies for more detail).

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Introduction

Mangroves around the world have been exposed to oil both from individual spills and from chronic pollution from refinery and storage tank discharges. Well-documented oil spills in mangrove areas provide us with a good idea of some of the complexities and variability of the impacts and response options. We have highlighted techniques (learned from field trials, toxicology, and laboratory studies) to measure the health of mangroves. With help from NOAA's IncidentNews.gov database and from colleagues around the world we searched for case studies of oil spills impacting—or potentially impacting—mangroves. We kept our focus on individual incidents and did not include cases involving long-term pollution. However, we know that some spills occurred at sites that had been impacted by spills in the past (Bahía las Minas, Panama and Roosevelt Roads, Puerto Rico). We also focused more on the direct and indirect effects of oiling and cleanup on the mangroves themselves, less on associated fauna and flora. The incidents include a wide range of documentation and a wide range of oil types. From these we identified several case histories that provided information about the incident, response methods, and long-term impacts and recovery. These are briefly reviewed below in chronological order.

One lesson that is quite clear from even a few of the cases is that the full extent of damage to mangroves is not apparent for many months or years after an incident, regardless of the fuel type and extent of response (other than full protection). Many questions remain about most studies. The most important is, How long does recovery actually take? Although a number of post-spill studies were conducted for as long as 10 to 20 years, we were able to find only a few reports where monitoring continued long enough to confirm full recovery.

Zoe Colocotronis, *La Parguera, Puerto Rico, 1973*

On March 18, 1973, the *Zoe Colocotronis* ran aground on a reef 3.5 miles off the La Parguera tourist area on the southwest coast of Puerto Rico. The master intentionally released 37,579 barrels (1.58 million gallons) of Venezuelan (Tijuana) crude oil. An estimated 24,000 barrels (1.01 million gallons) stranded on the beaches of Cabo Rojo. Three separate pools of black oil 6-8 inches thick oiled the shore of Cabo Rojo on the Bahía Sucia side. On March 21, a large number of sea cucumbers, conchs, prawns, sea urchins, and polychaete annelids washed ashore. Organisms died in the *Thalassia* seagrass beds and oil moved into mangrove forests composed of white, red, and black mangrove trees (Nadeau and Berquist 1977).

Response

Cleanup efforts were conducted outside the mangrove areas and involved booming, digging sumps, and pumping the collected oil into tank trucks. On March 23, before the oil in the mangroves could be recovered, an unexpected wind shift drove patches of oil out of the mangroves and into other areas and beaches. By March 24, 604,000 gallons of nearly pure oil had been removed from other areas using sumps, skimmers, and vacuum trucks. Steam cleaning was not used because there was no accessible source of fresh water. No cleanup was conducted in the mangroves.

Impacts

EPA scientists surveyed the mangrove areas for a week beginning 24 hours after the spill. Detailed surveys were conducted of all oiled areas during the second week after the spill and again during the thirteenth week. Additional EPA site visits were made in January 1974 (10 months later) and January 1976 (34 months later) providing some idea of long-term effects. In one well-studied area, one hectare of red and black mangrove trees was defoliated and died during the three years following the spill. However, the EPA scientists also noted that much of the associated invertebrate life had recovered (Nadeau and Bergquist 1977).

In November 1973, eight months following the spill, oil chemists from Bowdoin College in Maine visited several oiled sites and noted a re-emergence of young trees. Although sediment oil concentrations remained high, the oil was heavily weathered and degraded. These observations suggested that the toxic components were gone in about half a year. This team had also visited oiled black mangrove sites four times between April 1979 and April 1981, 6 to 8 years after the spill. The scientists measured ratios of sodium and potassium in some plants, supporting the idea that oil injured the trees by disrupting salt and water balance and that such disruption might have been alleviated by directed cleanup. However, they made no comment on the visible health of the mangroves at that time (Page et al. 1979; Gilfillan et al. 1981).

Eleven years after the spill other chemists took sediment cores from several previously oiled mangrove sites and found concentrations ranging from 10,000 to 100,000 ppm (dry weight, total unresolved hydrocarbons) in a layer 6 cm below the relatively clean surface sediments. In addition, they found oil, possibly from the 1962 *Argea Prima* spill, 14-16 cm below the surface. These last researchers did not report the status of the mangrove trees themselves (Corredor et al. 1990).

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Peck Slip, *Eastern Puerto Rico, 1978*

On December 19, 1978 the *Peck Slip* released between 440,000 and 450,000 gallons of Bunker C oil into open waters offshore of eastern Puerto Rico. Within two days oil had stranded in segments along 26 km of eastern Puerto Rico shorelines, mostly sand beach. However, some oil entered outer and inner fringing mangroves in three areas, and inner basin mangroves in one of these areas.

Response

No cleanup actions were undertaken although observers noted floating absorbent pads at one site. Surveys of mangroves were conducted shortly after the spill (December-early January 1979; Robinson 1979), about three months later (Gundlach et al. 1979), 10 months later, and 18 months later (Getter et al. 1981).

Impacts

Mangroves on a small island (Isla de Ramos) were lightly impacted (prop roots had a 15-cm band of oil 50 to 60 cm above the substrate) and apparently did not suffer long-term injury. Near Punta Medio Mundo, about 2.6 acres of inner fringe and inner basin mangrove roots were heavily oiled (prop roots with up to a one-meter band of oil) and two acres moderately oiled (0.3 to 0.45-m band of oil; Robinson, 1979). An estimated 3.5 tons of oil coated the mangrove roots. Algae growing on the prop roots absorbed the oil. Another two acres of mangroves at Pasaje Medio Mundo were moderately oiled with an estimated 1.3 tons of oil (prop roots oiled by a 0.2-meter band on oil).

Within two to three months the heavily oiled inner fringing and basin mangroves at the Punta Medio Mundo forest were defoliated. Prop-root oiling had widened to a band of over two vertical meters, possibly from oiled climbing crabs. Later site visits confirmed that mangroves with the most heavily oiled prop roots remained defoliated 10 and 18 months later (Getter et al. 1981).

This was one of five sites studied by Getter et al. (1981). From these studies the authors urged that inner fringing and inner basin mangroves receive highest priority for protection from oil spills.

Restoration

No restoration activities were undertaken at this spill.

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Figure 5.1 Oiled crab and snail on red mangrove trunk at the Peck Slip spill in 1979. (OR&R)

JP-5 Jet Fuel Spills, Roosevelt Roads, Puerto Rico (1968 and 1999)

In 1986 and again in 1999, Roosevelt Roads Naval Air Station storage tanks released JP5 jet fuel into a cove in eastern Puerto Rico. Before the 1986 and 1999 JP-5 spills, the area had been contaminated by oils from several past spills: a Bunker C spill in 1958 and a diesel spill in 1978, both from onshore storage tanks, and a 210,000-gallon diesel spill in 1981 from a tanker. All of these spills contaminated mangrove areas but effects of the earlier spills are unknown. In both recent cases, mangrove forests were contaminated, though response strategies differed markedly. Effects on mangroves were monitored at both spills.

On November 27, 1986, 59,000 gallons of JP-5 fuel washed down a catchment stream (tidal creek) and into Ensenada Honda. Two mangrove forest areas were contaminated, one in the tidal creek and the other at the head of the saltwater bay.

On October 20, 1999, 112,000 gallons of JP-5 fuel spilled from a day-tank at the U.S. Navy Base. The oil flowed into an underground drainage pipe, which runs under a runway and several roads for several hundred yards. The pipe empties into an open drainage ditch, which drains to a 12-hectare mangrove forest. This forest drains through a culvert into Ensenada Honda Bay.

Response

No cleanup actions were mentioned in reports dealing with the 1986 incident, presumably because of the high evaporation rate of JP-5 jet fuel in open conditions.

In the 1999 incident the Navy's primary environmental concern was the bay. In the face of an approaching hurricane, USN Construction Battalion (Sea Bees) personnel constructed a dam to plug the culvert between the first impacted mangrove (later named "mangrove A") and the mangrove adjacent to the bay (later named "mangrove C"). This dam trapped the water in mangrove area A. The final reports should be consulted for specifics as there were many details to the flow diversion response. Fuel was recovered, where practical, using under flow dams, skimmers, vacuum trucks, and sorbent materials. Attempts to manually remove oil with sorbents proved both ineffective and a human health risk for responders from inhalation of jet fuel fumes. It was estimated that 15 to 20% of the product was recovered, over 70 percent evaporated, and some 10 to 15% (approximately 11,200 - 16,800 gallons) remains unaccounted for; presumably stranded in the mangroves or in the sediments near the spill site.

The fuel flowed through the mangroves and some portion of the oil changed color from almost clear with a slight yellow tint to brown/black, similar to a light crude oil. It is unknown as to whether this was as a result of tannins from the mangroves dissolving into the oil or the JP-5, liberating heavier product remaining from previous spills.

Impacts

1986 Spill.

In the 1986 incident two mangrove areas were contaminated by JP-5 fuel: (1) the northernmost red mangroves drained by the tidal creek, and (2) the mixed species mangroves adjacent to the Coast Guard pier in Ensenada Honda. Local responders noted visible effects on adult trees within 10 days of oiling. Follow-on surveys were conducted in the second area 17 months later and again 23 months later. During these surveys 10 x 10-meter grids along transects documented tree height, canopy, tree death, percent open canopy, seedling counts, and invertebrate biota. There were three transects in oiled areas plus two in unoiled areas. In June 1987, false-color aerial photos were taken of the impacted forest.

Detailed surveys five months later found most adult trees in the oiled areas dead and/or defoliated. However, there were live seedlings with highest densities along the forest front. Furthermore, sediment oil concentrations were extremely low (less than 1 ppm) and similar to concentrations in unoiled areas. Because of the low impact on seedlings and the near-absence of fuel oil six months later, researchers concluded that there was no smothering effect from the jet fuel. Adult tree defoliation and mortality was likely caused by initial direct toxicity of the fuel to root structures.

Apparently these mangroves recovered sufficiently from the 1986 JP-5 spill to merit no comment from personnel responding to the 1999 spill, other than that they were protected by the response itself. Given the location of the 1999 contamination (tidal creek mangroves), very little cleanup was possible. However, the series of water diversion activities resulted in preventing oiling of the mangrove (C) in Ensenada Honda.

1999 Spill.

Tidal creek mangroves (areas A and B) were clearly damaged from the 1999 incident, due either to fuel toxicity or extended flooding, or both. Follow-up studies through October 2001 indicated that there was some recovery in the flooded area A two years after the incident, with new propagules and new shoots on injured trees. However, there were no signs of recovery in area B. Of a total of 50 acres of injured mangrove forest, about 30 acres showed no signs of recovery two years later (Csulak 2001).

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Vesta Bella *Oiling and Cleanup of U.S. Virgin Islands Mangroves, 1991*

On March 6, 1991, the barge *Vesta Bella* sank southeast of Trinidad, releasing an unknown amount of high aromatic No. 6 fuel oil. The barge continued to leak for more than 20 days. Some oil moved north, eventually stranding on several beaches on the north side of St. John, in the U.S. Virgin Islands. Beach surveys began there on March 23. Red mangrove oiling was not extensive: one-meter prop roots of individual or small groups of mangrove trees were oiled 30 to 35 cm above the substrate. However, the short (15 cm) prop roots of supratidal white mangroves were heavily coated. These trees were also stressed before the spill due to beach erosion.

Response

A modest level of cleaning was attempted with a planned revisit to the site a year later. Roots were carefully wiped by a select group of workers, and then snare boom was strung and allowed to scrub roots with the rise and fall of the tide. Snare boom was removed after 24 hours. One year after the spill the mangroves were revisited and measured for a variety of plant health indicators.

Impacts

The white mangroves at one site were heavily defoliated but also showed extensive new growth on both oiled and unoiled trees, growth that apparently began six to twelve months post spill. There was some sign of chlorosis and no signs of oil on roots. Close inspection of formerly oiled fringing red mangroves indicated these trees were healthy—fully foliated, with no signs of chlorosis. Only one tree was severely oiled and cleaned at the time of the spill: measurements indicated this tree was in good health.

Unfortunately, no oiled mangroves were left uncleaned, to serve as a reference, so it is difficult to ascribe the good condition of the trees one year later, to the cleaning. However, it is clear that this level of cleaning did not cause any mortality to the trees. The authors caution that this cleanup method was done in areas with a firm substrate. Finally, they confirmed that there was very little contamination of the substrate.

Restoration

No restoration activities were undertaken at this spill.

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T/V Era*, Spencer Gulf, South Australia, 1992*

On August 30, 1992, the tanker *Era* released an estimated 296 tonnes (974,000 gallons) of heavy Bunker oil (a blend of diesel and heavy residual) at a jetty near the head of Spencer Gulf, South Australia. On the night of September 1-2, an estimated 20 tonnes (5,500 gallons) stranded along 10-15 km of mangrove (*Avicennia*) forest south of Port Pirie, S.A. However, subsequent surveys estimated that the actual quantity stranded in the mangroves was 57 tonnes (15,600 gallons).

Response

Within two to three hours of the release, the oil slick was treated from vessels spraying dispersants Corexit 9527 and 7667; the following day, aircraft also sprayed slicks with Ardrox dispersant. Responders were advised that cleanup within the mangrove forest was not feasible and would likely increase damage to adjacent, unimpacted areas. Thus, all subsequent activity in the mangrove forest was restricted to detailed and long-term monitoring.

Impacts

Oiled mangroves were monitored for four years after the spill. This is perhaps one of the most well documented accounts available of the fate and effects of oil in a mangrove forest. Only a brief, highly simplified account can be given here and the reader is advised to consult the report for important details and qualifications (Wardrop et al. 1997).

Due to an extremely high tide, oil penetrated far into the mangrove forest (50 m) coating leaves as well as stems, trunks, and sediment. Oil concentrations and visible damage to mangrove trees were recorded over four years. About 75-100 hectares were oiled: 4.2 heavily, 7.3 moderately, and 38.0 lightly. In 1992 heavy oiling of canopy and extensive mats of oiled sea-grass debris characterized heavily oiled areas. By November 1992 mangroves over a total area of 2.3 hectares suffered extensive defoliation; the area expanded slightly to 3.2 hectares by 1995 and then stopped increasing. Trees that were totally defoliated did not recover during the four-year period. Defoliation and degree of sediment oiling were correlated: heavily oiled areas were completely defoliated and moderately oiled areas were "severely" defoliated. In lightly oiled areas trees had less leaf damage and recovered rapidly. "Overall the extent of damage in each of the studied locations, and the speed with which it occurred, has correlated to the oiling classification assigned in the first survey" (Wardrop et al. 1997). Finally, the veracity of the original recommendation of "no cleanup" was supported: injury to mangrove trees was restricted to those initially impacted by moderate to heavy oiling.

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Witwater *and Texaco Storage Tank Spills, Bahía Las Minas, Panama, 1968 and 1986*

Two large oil spills, 18 years apart, resulted in long-term injury and recovery to a portion of the 1,200 ha of mangroves of the Bahía Las Minas area of Panama.

***Witwater*.** On December 13, 1968, the oil tanker *Witwater* broke up in heavy seas off the Atlantic coast of Panama, spilling 14,000 barrels (588,000 gallons) of Bunker C and diesel oil into the water 5 miles from Galeta Island. Strong seasonal winds pushed the slick towards the island, oiling sand beaches, rocky coasts, and mangroves.

Texaco Storage Tank. On April 27, 1986, a Texaco storage tank at a refinery on Isla Payardi, Panama, ruptured, releasing approximately 240,000 barrels (10.1 million gallons) of medium-weight crude oil. Approximately 140,000 barrels (5.9 million gallons) of oil flooded through a dike and overflowed separators and a retaining lagoon and flowed into Bahía Cativá, an arm of Bahía las Minas.

Responses

***Witwater*.** Several thousand barrels were pumped from the waters surrounding Galeta Island, and approximately 5,000 barrels (210,000 gallons) were ignited and burned along shorelines in the bay. By December 17, pumping and shoreline burning cleaned up approximately half of the spilled oil.

Texaco Storage Tank. Refinery personnel reported that 60,000 barrels (2.52 million gallons) of oil were recovered. It is not known how much of this recovered oil was from the sea. Dispersants were applied in Bahía Cativá, Islas Naranjos, offshore of Bahía Las Minas, near Portobelo, and along the northern breakwater at the mouth of the Panama Canal. Although dispersants appeared to be ineffective due to the weathered state of the oil and the calm seas, skimmers recovered some floating oil. Vacuum trucks were used as part of the shore-based cleanup effort. Several channels were dug through the mangroves to drain the oil. These channels appeared, instead, to have helped move the oil inshore. Increased disturbance due to the construction of the channels may have also contributed to subsequent erosion. Oiled rocks and debris were manually removed along the more accessible shorelines. Seawater was sprayed on some sandy areas to aid oil removal. Pumping to recover floating oil appeared to be the most effective oil recovery method. The shallow waters and mangroves rendered many oil spill cleanup techniques impractical.

Impacts

Archived aerial photographs (1966, 1973, 1979, and 1990) and ground surveys were keys to understanding the effects of these two spills on mangrove forests.

Witwater. Despite the cleanup, both red and black mangrove trees were severely oiled, and the majority of the red mangrove seedlings were killed. Oil also damaged many of the mangrove forest inhabitants. Initial reports did not indicate that adult trees had suffered. Aerial survey photos from 1966 and 1973 were used to assess deforestation, oil gaps, and open canopy. About 49 hectares of mangrove forest (representing 4 percent of the total mangrove forest) had been completely deforested in 1973 (five years after the spill). Most deforested areas had new recruits by 1979 (eleven years after the spill) but 3 ha were lost to sea-margin encroachment. Observable differences (oil gaps, and canopy height and structure) and oiled sediment persisted into 1992, 23 years after the *Witwater* spill.

Texaco Storage Tank Spill. The distribution of oil was surveyed from aircraft for two months following the release. A total of 51 miles of shoreline was heavily oiled, including some mangroves recovering from the *Witwater* spill. In a central embayment (Bahía Cativá), approximately half the surrounding forested area (and halfway up the intertidal zone) was killed. Oiled habitats within this distance included extensive mangroves, intertidal reef flats, seagrass beds, and subtidal coral reefs. Re-oiling of the shoreline and mangroves was a continuing problem. Oil slicks were regularly observed within Bahía las Minas for at least four years following the spill with oil coming predominantly from areas of fringing mangroves. As the oiled red mangrove trees decayed, it was believed that eroding, underlying sediments released trapped oil.

An affected reef flat habitat was the site of an ongoing study at the Smithsonian Tropical Research Institute's field station at Punta Galeta. A detailed study of mangrove trees revealed that one- to two-year-old seedlings appeared to survive whereas the surrounding adults died. It was believed that, somehow, young seedling structure (perhaps lack of prop roots) enabled the young trees to tolerate periods of oil immersion. It was suggested that the disruption of the substrate before replanting may remove such survivors, hampering forest recovery. Oil persisted in the mangroves through May 1989. Initial oiling of the trees produced measurable amounts of oil on 100% of all the roots that were sampled. Through May 1989, the mangrove roots in the open coast and channel areas showed 70% oiling, while the oiled proportion in the stream mangroves remained 100% oiled. The decrease in oil coverage resulted from weathering, microbial degradation, and loss of oiled bark or encrusting organisms. Root mortality was greater in oiled areas.

Subsequent aerial and ground surveys indicated "recovery of the 1986 spill was well-advanced by 1992" (Duke et al. 1997) due, in part, to extensive restoration. However, about 5 hectares of fringing forest were lost to sea-margin encroachment and there remained important differences between sheltered and exposed areas.

Although ten times more oil was spilled in 1986 than in 1968, this did not result in ten times more damage to mangroves. Calm winds, lower tides, different oil type, and longer weathering time before impact may have resulted in less toxicity.

Restoration

Because of extensive mangrove mortality, several replanting projects were conducted at Bahía las Minas, in hopes of speeding mangrove forest recovery, which was at the time estimated to take 20 years or longer (Teas et al. 1989).

Experiments to determine whether propagules could survive if planted directly in oiled sediment found 100% mortality up until six months post spill. By nine months post-spill, propagules survived at rates similar to those at unoiled sites. Beginning 12 months after oiling, red mangrove seedlings that had been raised in a separate nursery area were planted (with added fertilizer) in areas of the damaged mangrove forest. A total of 42,000 nursery plants and 44,000 propagules were planted.

Studies conducted in 1989 (33 months post-spill) looked at the effectiveness of the plantings conducted in 1987, by comparing mangrove densities in areas that had recruited naturally with those that were replanted. Though planted seedlings had survived in all areas studied, naturally recruited plants were most dense. Thus, natural recruitment was more effective at recolonizing oil-damaged areas and, over time, natural recruits out-competed planted seedlings. Researchers also noted detrimental collateral impacts from planting, including cutting and removing dead timber for boat access (which removed shelter for seedlings), trampling sediments, digging holes (which accelerated erosion), and damaging existing seedlings (Duke 1996). Overall, planting did not result in a net benefit to the mangrove forest. However, since recolonization of mangroves was lowest in exposed areas, Duke suggests that an effective restoration activity could be to protect very exposed areas until mangrove trees are well established.

For Further Reading

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Bouchard *Barge* B-155*, Tampa Bay, August 1993*

On August 10, 1993, the freighter *Balsa 37*, the barge *Ocean 255*, and the barge *Bouchard 155* collided in the shipping channel west of the Skyway Sunshine Bridge and south of Mullet Key in Tampa Bay, Florida. The collision caused three separate emergencies: (1) the *Balsa 37* was listing, threatening to spill phosphate rock; (2) the jet fuel, gasoline, and diesel caught fire on the *Ocean 255*; and (3) the *Bouchard 155* was holed at the port bow, spilling approximately 8,000 barrels (338,000 gallons) of No. 6 fuel oil into Tampa Bay. By August 15 most of the floating fuel oil had come ashore and heavily coated sand beaches, several mangrove islands, and seawalls within Boca Ciega Bay. By August 16 very little floating oil was seen offshore. In the shallow, low-energy areas along the mangrove islands inside Johns Pass and at a few locations in the surf zone, oil had mixed with beach sand and shallow sediments to form underwater tarmats, some of which came ashore on the mangrove keys.

Response

The No. 6 fuel from the barge is the only material known to have been released from this incident. Countermeasures used during this spill were mechanical or manual. Skimming operations were used to collect free-floating oil. Efficiency and effectiveness of skimming operations were extremely high. Oil in and around mangrove islands was removed by vacuuming. Areas were left oiled when it was felt that cleanup methods would cause greater impact than leaving the oil in place. Some of the submerged oil in very shallow areas was removed using buckets and shovels. Oiled seagrass beds were cleaned by gently lifting oil out of them by hand. "How clean is clean" inspections for mangroves, seagrass beds, and other sensitive areas were judged on a case-by-case basis by the inspection committee.

Impacts

Tarmats formed when sediment was mixed with oil along the shallow flats surrounding the islands. Large, thick mats coated mangrove roots, oyster and seagrass beds, and tidal mud flats. Much of this oil was vacuumed out using vacuum transfer units on grounded barges staged around the islands and shallow areas.

Scientists visited oiled and unoiled mangrove keys quarterly between November 1994 and April 1996. Individual trees, pneumatophores, and prop roots were tagged to enumerate trends in defoliation, leaf health, shoot number and length, and mortality of juvenile and adult plants or their structures. Visual oiling trends were documented through late 1995 and sediment samples for wet chemistry collected in 1996. Adult red mangrove trees at the most heavily oiled site (outer Eleanor Island) deteriorated over this time period, with moderate to heavy defoliation and soft, rotting prop roots. "Of marked trees, 20% were totally defoliated and appeared dead by June 1994" (Levings and Garrity 1995). Nine-month mortality of juvenile red and black mangrove plants was 5% at unoiled reference sites, 35% in heavily oiled areas on the protected side of the island and 50% in heavily oiled areas on the exposed side of Eleanor Island. It was predicted additional mortality would continue to occur.

The researchers also measured for signs of sublethal stress in adult trees: one to two years after the spill and cleanup, surviving red mangroves experienced graded negative responses in four measures of shoot growth and production, suggesting that sublethal long-term effects may be common in oiled mangroves. Sediments around trees experiencing these responses contained greater than 500 ppm total hydrocarbons (dry weight).

More follow-up observations are needed at these sites, but we are not aware of any extending beyond three years after the spill and cleanup.

Restoration

Trustees from state and Federal agencies and the responsible party developed a restoration plan for mangroves and associated habitats damaged in the spill. A compensatory plan provided mangrove and associated wetland habitat for fish, birds, and epibenthic communities at a site in the same watershed but not necessarily actually impacted by the spill.

The responsible party purchased a former dredge disposal site in Boca Ciega Bay and deeded it into public ownership. This site contained degraded mangrove forest that was restored through increased tidal exchanges and removal of exotic plants and debris. On the bayward edge of the mangrove forest, smooth cordgrass (*Spartina alterniflora*) was planted to create a fringing saltmarsh buffer that could eventually provide habitat for mangrove seedlings. A monitoring program was established with specific "success" criteria outlined, including vegetative cover and height of mangroves, absence of exotic species, and functional tidal exchanges.

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Mangrove Glossary

Aerial roots – Roots that are formed in and exposed to air. In mangrove species (e.g., *Rhizophora* spp.), aerial roots develop into stilt roots (prop roots and drop roots) that anchor into the sediment, offering mechanical support and nutrient absorption.

Anaerobic – Occurring with little or no oxygen.

Anchialine ponds – A rare Hawaiian ecosystem, consisting of pools with no surface connection to the ocean, but affected by tides. These pools have a characteristic water quality and support an assemblage of animals and plants, many of which are endangered.

Anoxic – Without free oxygen. Aerobic metabolism (e.g., bacterial respiration) can consume dissolved free oxygen in water and soils, resulting in anoxic conditions that are detrimental to oxygen-breathing organisms.

Bioaccumulate – Uptake of dissolved chemicals from water and uptake from ingested food and sediment residues.

Biogenic – In mangroves, the trees themselves create the habitat. Biogenic also means "resulting from the actions of living organisms."

Canopy – topmost layer of leaves, twigs, and branches of forest trees or other woody plants.

Chlorosis – abnormal condition characterized by the absence of green pigments in plants, causing yellowing of normally green leaves.

Defoliation – The removal of the foliar tissues of a plant, resulting from mechanical (e.g., hurricanes), biological (herbivore), or chemical agents (e.g., plant hormones).

Deposition – The accumulation of material on a substrate. In mangrove systems this term is typically used in relation to accumulation of surface sediment.

Detritus – Non-living organic matter that is so decomposed that it is impossible to identify the original parent material.

Drop roots – Roots that develop on a branch and begin as aerial roots but eventually grow into a substrate; these roots can provide mechanical support (e.g., *Rhizophora* spp.).

Endpoint – A measured response of a natural resource to exposure to a contaminant, such as oil, in the field or laboratory.

Eustatic sea level rise – The worldwide rise in sea level elevation due mostly to the thermal expansion of seawater and the melting of glaciers.

Evapotranspiration – The transfer of water from the soil, through a plant, and to the atmosphere through the combined processes of evaporation and transpiration. Evaporation is a function of surface area, temperature, and wind. Transpiration is a process of water loss through leaf stomatal openings, and is related to gas exchange and water transport within a plant. When the stomates open, a large pressure differential in water vapor across the leaf surfaces causes the loss of water from the leaves.

Genotype – Genetic makeup of an individual organism.

Hermaphroditic – Both sexes present in an individual organism.

Infrared photography – Photography using films sensitive to both visible light and infrared radiation. Live vegetation is particularly highlighted with infrared films and so is a useful tool for aerial surveys of live and dead plants.

Lenticel – A small, elliptical pore in the periderm that is a means of gaseous exchange.

Mangal – a mangrove forest and its associated microbes, fungi, plants, and animals.

Mangrove – a tree or shrub that has evolved the adaptations for growing in the intertidal zone (specifically, adaptations to salinity and flooded conditions).

Microtidal – A tidal range of less than one meter.

PAH – polynuclear aromatic hydrocarbon; also called polycyclic aromatic hydrocarbon, a component of oil. PAHs are associated with demonstrated toxic effects.

Pneumatophore – A vertical extension of an underground root, with lenticels and aerenchyma to allow for gas exchange. Pneumatophores are characteristic of trees adapted to flooded conditions (such as *Avicennia* spp.)

Prop roots – Roots that develop on a trunk and begin as aerial roots but eventually grow into a substrate; these roots can provide mechanical support (e.g. *Rhizophora* spp.), sometimes called "stilt roots."

Propagule – Seedling growing out of a fruit; this process begins while the fruit is still attached to the tree. For some species of mangroves, propagules represent the normal, tidally dispersed means of reproduction.

RSLR – relative sea level rise - The net effect of eustatic sea level rise and local geomorphoplogical changes in elevation. Local subsidence can make apparent RSLR much greater than eustatic rise.

Sublethal effect – An effect that does not directly cause death but does affect behavior, biochemical or physiological functions, or tissue integrity.

Vivipary – The condition in which the embryo (the young plant within the seed) germinates while still attached to the parent plant (synonymous with viviparity)

Weathering – Changes in the physical and chemical properties of oil due to natural processes, including evaporation, emulsification, dissolution, photo-oxidation, and biodegradation.

Wrack – Organic material, usually from dead seagrass or algae that wash up on shorelines.

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