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 shortor 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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