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Managing Oil Spills in Mangrove Ecosystems: Effects, Remediation, Restoration, and Modeling

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Oil Spills and Mangroves: An Overview

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INTRODUCTION

The term mangrove refers to a non-taxonomic grouping of woody, halophytic spermatophytes that occur along low-energy coastlines, deltas, estuaries, and embayments throughout the tropics and subtropics. Tomlinson (1986) recognizes 54 "true or strict" species of which the members of the Rhizophoraceae and Avicenniaceae are the most widely distributed. Since they dominate coastal intertidal areas that are subject to stranding and trapping of oil, a number of researchers (cf. Hayes and Gundlach 1979) consider mangroves to be the most sensitive of all coastal ecosystem types to oil spills. In this regard, Odum and Johannes (1975) speculated that mangroves would take many decades to recover from oil spills. The early research on the topic, however, focused almost exclusively on post-spill damage assessments, in which the primary objectives were to determine the spatial area of impact, and the intensity or degree of acute damage on the impacted flora and fauna (e.g., Lewis 1979, 1980; Getter et al. 1980a,b; Getter et al. 1981). This type of post-spill research has been loosely referred to as the "dripping oil and dead-body count approach." As argued in this review, the observable acute damage following a spill may be insignificant when compared to the longer-term chronic stress induced in mangroves and the contiguous nearshore fauna and flora by the residual oil.

The following summary of acute, secondary and chronic consequences is based primarily on: (1) a review of 28 oil spills in the Caribbean and Gulf of Mexico region (see earlier listing in Getter, Snedaker and Brown 1980c), (2) a number of independent studies (Chan 1977; Page et al. 1979; Gundlach, Scott and Davis 1979; Gundlach et al. 1979; Getter et al. 1980a,b; Odum and Johannes 1975; Hayes, Gundlach and Getter 1980; Lugo, Cintron and Goenaga 1981; Snedaker, Jimenez and Brown 1981; Garrity, Levings and Burns 1994; Burns et al. 1994; Levings, Garrity and Burns 1994), (3) reports of experimental research findings (Jagtap and Untawale 1980; Getter 1983; Ballou et al. 1987; Thomas 1987; Rielinger 1991; Teas et al.,1993), (4) personal observations of the author, and (5) personal communications with knowledgeable persons.

EFFECTS OF STRANDED OIL IN THE MANGROVE ECOSYSTEM

Acute Consequences

The effects of the physical stranding of oil in intertidal mangrove habitats is largely dependent on the oil type, the elapsed time between a spill and its stranding, wind and current conditions, and tidal stage. With regard to oil type, the more highly refined products tend to be relatively more toxic, but because they are also relatively volatile, they are quickly dissipated. The volatile fractions (e.g., naphtha, benzene) are also lost from the heavier oils that remain at sea for extended periods of time prior to stranding. In these regards, the stranding of relatively weathered oils that are depleted in the lighter fractions has a lesser potential to produce acute toxic effects than "fresh" oil and the highly refined products. Whether or not refugee oil eventually becomes stranded along the shoreline is highly dependent on the ambient wind and current conditions. For example, longshore winds and currents tend to move oil parallel to the shoreline, painting long stretches of the seafront, whereas strong onshore winds tend to push the oil onto a smaller length of shoreline but also further inland. Similar to wind-driven oil, oil arriving at the shoreline on incoming tides has the potential to reach deeper into intertidal and supratidal habitats. However, it also has a greater potential for washout on the retreating tide except when trapped in paludal depressions inland from the shoreline fringe. Tidal patterns are particularly important in the context of potential stranding. For example, in south Florida mean sea level is some 20 to 30 cm higher during the Fall than in the Spring (Wanless 1982) meaning that higher water levels in the latter part of the year contribute to a greater potential for inland stranding and trapping, but may also contribute to washout and removal from the intertidal zone (vide Levings et al. 1994).

Mangrove mortality tends to be highest among propagules, seedlings and juvenile trees, due to their proximity to the oil spill surface, and the potential for heavy and repeated oiling on both incoming and outgoing tides. Notwithstanding the potential for relatively intense oiling, shoreline seedlings sometimes survive the initial oiling event. Lugo, Cintron and Goenaga (1981) suggest that mangrove seedlings may be more stress resistant than adult trees based in parts on their field observations and certain of the physiological differences reported by McMillan (1974). In this regard, young-of-the-year seedlings of *Rhizophora* and *Avicennia* utilize cotelydenary reserves prior to developing an extensive root system. This may mitigate against uptake of toxic compounds.

The reported rapid mortality of mangroves following a spill is assumed to be due to mechanical suffocation and the cessation of gas exchange processes associated with the rhizosphere. However, this is somewhat equivocal for two reasons. First, one of us (SCS) has observed and photographed, heavily-oiled prop roots having clean, and presumably active lenticels. To the extent that gas exchange is relatively unaffected, "suffocation" may not be the primary cause of mortality. Secondly, in laboratory experiments using freshly excised *A. germinans* pneumatophores (which also have gas-exchange lenticels), nitrogen gas (N_2) was still able to be transported through the oil film covering pneumatophores (Melvin S. Brown, pers. comm.). Rielinger's (1991) followup work on O_2 uptake and CO_2 fluxes in excised pneumatophores indicated that oil viscosity was the principal factor in gas exchange; the heavier oils reduced exchange to a greater extent than lighter oils.

Further in this regard, since heavy oiling of roots, pneumatophores, tree trunks and sediment can cause direct mortality (or be highly damaging, see 1994 article by Levings, Garrity and Burns), an experiment was conducted on the effects of crude oil (Prudhoe Bay) and a dispersant in Panama in December 1984 (Ballou et al. 1987). In that TROPICS (Tropical Oil Pollution Investigations) field experiment, coastal sites with contiguous mangroves, seagrass, and corals were acutely exposed to untreated crude oil and chemically dispersed crude oil. After 2.5

years of monitoring, the authors concluded that untreated crude oil had severe, long-term effects on the intertidal mangroves and associated fauna, but only minimal effect on the subtidal (continuously submerged) seagrasses and corals. In contrast, the chemically dispersed oil minimized damage to intertidal mangroves but caused "relatively severe, long-term effects on the coral and seagrass environments". In a subsequent study ten years later (Dodge et al., in press), effects of the crude oil on mangroves were still evident in terms of a lower than expected increase in the mean trunk diameter of affected trees, a reduced canopy foliage density and corresponding increased canopy light transmission, increased leaf thickness, and altered patterns of new leaf production and senescent leaf loss.

More recently, Teas et al. (1993) tested one of the newer, less toxic, non-dispersing shoreline "cleaners" (Corexit 9580) on experimentally oiled (bunker C fuel oil) red mangroves (*R. mangle*). They concluded that it was effective in minimizing morbidity and mortality but only if used within a few days of an oiling event. However, in a more recent field study, Quilici et al. (1995) concluded that shoreline cleaners negatively affected the productivity of *R. mangle* leaves on the treated trees, suggesting a sublethal effect not observed in acute mortality studies. Since there are now a number of non-dispersing cleaners on the market, research is needed to evaluate both their efficacy and sublethal chronic effects on other mangrove species, and subtidal organisms, such as seagrass and coral communities.

One acute and severe consequence of the mass mortality of mangroves following a spill event is the death and decomposition of the underground root mass. Since the root mass in the *Rhizophora* and the *Avicennia* represents 40 to 60 percent of the total forest biomass (Snedaker 1995: Snedaker et al. 1994), its loss results in significant subsidence in peat environments and erosion in sandy environments. Nine years following the TROPICS oiling experiment, the forest destruction and the ground surface elevation loss (-8.8 +/- 0.69 cm) were so great that the affected site exhibited the appearance of having been subjected to an "explosion" (Bart Baca, pers. comm.), an observation that was confirmed during the ten-year follow-up study (Dodge et al. in press).

Secondary Consequences

Mangrove mortality and the expression of stress symptoms may be delayed for one to several years period following an oil spill for reasons that may be related to: (1) the persistence of toxic petrogenic compounds in the sediment, and (2) the weakened state of the trees that makes them susceptible to other stressors. For example, following the M/V Howard Star spill in October, 1978, in Tampa, Bay, Florida (Lewis 1979; Getter et al. 1980c), 25 heavily oiled mangrove trees were tagged for long-term monitoring. However, only three of the identified trees exhibited a response (one died and two exhibited stress symptoms), whereas others, not originally identified as heavily oiled, died in mass (Lewis 1980). One of us (SCS) also observed a number of non-tagged dead trees at the same spill site following a severe freeze three years later in January of 1981.

In the earlier M/V Zoe Colocotroni spill in Puerto Rico, observers reported mangrove recruitment at the spill site, and presumed that it was evidence of recovery that later proved to be incorrect. In that instance, mangrove propagules from unaffected or surviving trees colonized the area and developed to the point where their cotyledonous reserves were exhausted; they then perished in mass (Ariel Lugo, pers. comm.). Also, in the subsequent spill litigation, confusion surrounded the question of the exact cause of mortality since the affected area was also subject to natural hypersalinity (Commonwealth of Puerto Rico 1973, 1978; Lugo et al. 1981). These examples suggest that otherwise healthy-appearing mangroves that are exposed to other stressors have a significantly higher probability of morbidity and mortality following exposure to oil (see supporting review and citations in Lugo et al. 1981).

Although the majority of the oil spill literature documents the adverse effects of oil on mangroves, some workers have documented an apparent "stimulating" effect (cf. Page et al. 1979; Thomas 1987). Thomas (1987) recorded an apparent stimulation in 28 experimental treatments versus inhibitory responses in 75 experimental treatments (Appendix A). It was also observed at the TROPICS site in Panama that mangroves regenerating on oil contaminated sediments were healthier and growing faster than similar-sized *R. mangle* at a nearby control station (Dodge et al., in press). Notwithstanding, Thomas argued that any deviation from the "normal" condition is an indication that the oil interfered with normal growth processes and development patterns (see also Getter 1983). To date no one appears to have addressed any of the ecophysiological questions that explicitly pertain to how oil interacts with the physiology of mangroves over the longer term.

Chronic Consequences

As stated earlier, the majority of the research on oil spills focuses on the immediate post-spill acute effects usually because of, and in preparation for, impending litigation. With the notable exception of the published research years after the large oil spill at Bahia las Minas, Panama, in 1986 (cf. Duke and Pinzon 1993; Garrity et al. 1994; Burns et al. 1994; Levings et al. 1994), almost nothing is documented concerning the long-term impact of oil spills in mangrove-dominated habitats. In that context, one has to wonder how legal damage levies (based on acute impact) would be altered if the chronic effects were also taken into account.

In addition to the above citations, the persistence of oil in sediments at oil spill sites years to decades after the spill event has been noted by a number of authors and observers (Mackin 1950; Corredor et al. 1990; Teal et al. 1992; Burns et al. 1994). Disturbance of the oil impregnated sediments, for example, by tidal action, storm pounding, decomposition of the organic substrate, or walking on the sediment (Teas et al. 1989), causes the release of oil in the form of a surface sheen or slick that was termed "bleedwater" by Mackin (1950). Whereas this phenomenon appears to be common in coastal marshes and mangroves, no one appears to have made a determination of the composition of the refugee bleedwater or speculated on the consequences for intertidal and nearshore marine life. Notwithstanding, oil in the form of bleedwater slicks has the ability to scavenge and concentrate organochlorine pesticides and other polar toxic water-insoluble compounds including chellated metals (Seba and Corcoran 1969; Hartung and Klingler 1970; Harvey et al. 1972; Hardy et al. 1987; von Westernhagen et al. 1987). This chemical scavenging and concentrating process could presumably cause the refugee oil bleedwater to become increasingly more toxic over time.

With regard to the heavy metal components in oil, particularly in crude, no one appears to have examined this factor, notwithstanding that mangroves can take up and concentrate metals in leaf tissue at concentrations significantly above background (cf. Carter et al. 1973; Tripp and

Harriss 1975, Peterson et al. 1979; Walsh et al. 1979; Snedaker and Brown 1981, Thomas and Ong 1981, Harbison 1986). Snedaker and Brown (1981), for example, reported the following metal concentration factors (relative to ambient concentrations) for leaves of mature mangroves in southeast Florida: chromium 5-6x, copper 1-2x, iron 2-3x, lead 4-5x, manganese 3-4x, nickel 4-5x, and zinc 1-2x. Although mangroves are relatively resistant to metal toxicity (Walsh et al. 1979), leaves enriched in metals could represent a source of metals entering detrital based marine food webs.

Similar to the metals, the uptake and accumulation of the aromatic fractions in spilled oil might also represent a subtle contamination of the leaf detritus food resource. In an experimental study, Thomas (1987) found that *R. mangle* synthesizes a range of biogenic aliphatic hydrocarbons from C14 to C29 dominated by odd-number compounds with the highest concentrations occurring among C23, C25 and C27-29 compounds. In contrast, the natural presence of aromatic compounds was found to be low. In the experimental dosing study, Thomas found a number of aromatic compounds in leaf tissues and that they closely matched the aromatic composition of the treatment oil. It was also reported that tissue concentrations were inversely proportional to the molecular weight of individual aromatic compounds.

SUMMARY

The principal conclusions that can be drawn from published articles and reports of post-spill evaluations and damage assessments are summarized as follows:

* Light weight refined oils and the volatile components of the heavier oils, including crude oil, are the most toxic, but are also the most susceptible to rapid dissipation, mainly by vaporization.

* Refugee oil that enters and leaves the mangrove habitat on the surface of tidal waters, "paints" the vegetation above the substrate but causes minimal ecological damage.

* Refugee oil that is stranded by wind or current within the mangrove habitat over successive tidal cycles, comes in direct contact with the sediment and surface litter where it becomes trapped. Over time, the oil moves downward into the sediment by gravity and tide-driven hydraulic draw down, where it may persist for decades.

* Oil impregnated sediments continually release small quantities of oil in the form of bleedwater, the ecological consequences of which are unknown.

* The removal of oil impregnated sediments to mitigate against acute and chronic damage is considered to necessarily be more damaging to the habitat than taking no action. Likewise the use of the new shoreline cleaners, once thought to be a viable option, has recently been questioned.

* The most visible ecological effect of stranded oil is the acute mortality of juvenile and adult mangrove trees and the associated fauna, within a period of several days.

* Juvenile and adult mangrove trees that survive an oiling event may experience morbidity and mortality if exposed to an unrelated stressor such as severe cold temperatures or draught.

* Sublethal effects of an oil stranding event are still detectable and measurable in a mangrove forest habitat for years to over a decade later even when the forest visually appears to have fully and completely recovered.

* Results from experiments and field assessments indicate that under certain circumstances, albeit poorly defined, petrogenic compounds can have a significant stimulating effect on mangrove growth and development.

* Because of the long-term ecological consequences, actions, such as booming and skimming, to prevent oil stranding within the mangrove habitat is often the preferred counter measure to be taken in the event of an oil spill.

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