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Decrease in osmotically driven water flux and transport through mangrove roots after oil spills in the presence and absence of dispersants

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ABSTRACT

The objective of this study was to evaluate the effect of crude oil on water transport through mangroves roots in the presence and absence of dispersants. Water transport through the roots were evaluated experimentally using red mangrove root segments exposed to salt water contaminated with Louisiana crude oil for seven days in the presence and absence of Corexit 9500A (dispersant). Experimental observations were interpreted in view of the structural integrity and fouling phenomena observed on the epidermis and endodermis layers of the roots. The effects of oil on the radial water flux through the epidermis and endodermis were analyzed using a dual layer filtration model. Progression of fouling due to accumulation and penetration of the contaminants through the root layers were interpreted in relation to observed mangrove health (long and short term effects) reported in the literature.

1. Introduction

Mangroves are trees and shrubs with aerial roots that grow in intertidal coastal sediments which provide shelter for highly diverse organisms (Lee, 2008; Rondinelli and Barros, 2010). Due to their partially submerged root systems, mangroves are vulnerable to oil pollution (Suprayogi and Murray, 1999; Sodre et al., 2013). The response of mangroves to oil spills differ due to differences in the hydrologic characteristics of the mangrove sites and the mangrove ecosystems that affect the persistence of oil in the mangrove habitat (Burns et al., 1993; Duke et al., 1997; Klekowski et al., 1994; Tam et al., 2005; Getter and Lewis, 2003). Mangrove forests with limited water mixing by waves, currents and tidal effects are likely to be more severely affected due to longer persistence of oil in the water (Böer, 1993; Burns et al., 1993; Lewis et al., 2011; NOAA, 1994). The impact characteristics and recovery of mangroves after oil spills can be described in four stages (Da Silva et al., 1997), even though the timeframes vary in different mangrove systems depending on the conditions (e.g., water mixing, type of oil). These include: 1. initial impact, which lasts about 1 year during which propagules and young plants are most likely to die; 2. structural damage which lasts about 2.5 years and trees begin to die; 3. stabilization which lasts about 5 or more years during which deterioration ceases with no noticeable improvement; and 4. recovery when the system improves via colonization and increased density.

Mangroves maintain a negative pressure in the xylem (−28 to −58 atm), which counteracts the osmotic pressure of the seawater (25–30 atm) (Scholander, 1968). Therefore, in view of the pressure available, water uptake by the mangrove roots can be considered as similar to that of the membrane filtration process. When water has a relatively small concentration of contaminants, the flux decline follows a linear pattern. However, at high contaminant concentrations, the water flux shows an exponential decline. The flux decline can be attributed to concentration polarization, adsorption of contaminants, pore blockage, and gel layer formation (Tansel et al., 2000). Concentration polarization and gel layer formation occur on the filter surface. During the filtration of oil contaminated water, there is almost always a gel layer forming on the membrane surface (Tansel et al., 2000, 2001) which reduces the water flux. Since the gel layer has a small diffusion coefficient and consists primarily of hydrophobic compounds, it is difficult for the large molecules in the gel layer to transfer back into the solution. Water may pass through the gel layer at a very slow rate by diffusion rather than by hydrodynamic transport mechanisms. Sequential membranes can be used to reduce fouling rate of the subsequent filters (Tansel et al., 2005).

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The objective of this study was to evaluate the effect of crude oil on water transport through the mangroves roots in the presence and absence of dispersants. Water transport through the mangrove roots were evaluated experimentally using red mangrove (*Rhizophora mangle*) root segments exposed to salt water contaminated with fresh Louisiana crude oil in the presence and absence of Corexit 9500A, which is a commonly used dispersant after major oil spills at sea. Experimental observations were interpreted in view of the membrane fouling process which limits the water flux. The effect of oil contamination on water flux through the mangrove roots were analyzed using a dual layer filtration model corresponding to the epidermis and endodermis layers in the mangrove roots. Fouling rates of the epidermis and endodermis and the progression of loss of water transport were evaluated and interpreted in relation to the observed mangrove health after oil spills reported in the literature.

2. Materials and methods

2.1. Experimental work

Experiments were conducted in the laboratory to evaluate the effect of crude oil contamination on water transport through the mangrove roots. Instant Ocean Sea Salt (Aquarium System, Mentor, Ohio, USA) and de-ionized water was used to prepare the salt water solution at 34 ppt. The Louisiana crude oil (Mississippi Canyon Block 252) was supplied by BP America Production Company in Houston, Texas, USA. The dispersant, Corexit 9500A, used in this study was supplied by Exxon/Nalco Energy Chemicals, Sugar Land, Texas, USA. Table 1 presents the solutions used.

The solutions were prepared in the 250-mL Erlenmeyer flasks. The Erlenmeyer flasks were sealed with parafilm and stirred by hand until the solution was mixed. A 6-inch segment of the red mangrove root sample was placed in each flask in the vertical position, partially submerged; sealed with parafilm and left for 7 days without any disturbances, as shown in Fig. 1a. After one week, the root samples were removed and examined destructively (by cutting in horizontal and vertical directions).

During the preliminary experiments, it was observed that one week of exposure time was adequate for analysis of the impacts of water transport through the roots. When the root samples were left in the solutions for longer than one week, same samples had noticeable mold growth on the top surfaces of the roots. Therefore, the exposure time was limited to one week.

2.2. Model development

The water flux through the mangrove roots can be considered similar to that of membrane filtration through a series of membranes. The range of hydrostatic pressure available for water transport through the mangrove structure (Fig. 2) is similar to that of nanofiltration. For membrane transport processes, flux is directly proportional to the driving force (pressure) and inversely proportional to the resistance.

Table 1
Solutions used for the mangrove root exposure experiments.

Sample	Salt water solution (mL)	Louisiana crude oil (mL)	Dispersant[a] (mL)	DOR[b]
1	150	–	–	–
2	150	1	–	–
3	150	1	0.2	1:5
4	150	1	0.1	1:10
5	150	1	0.05	1:20

[a] Corexit 9500A.
[b] Dispersant to oil ratio.

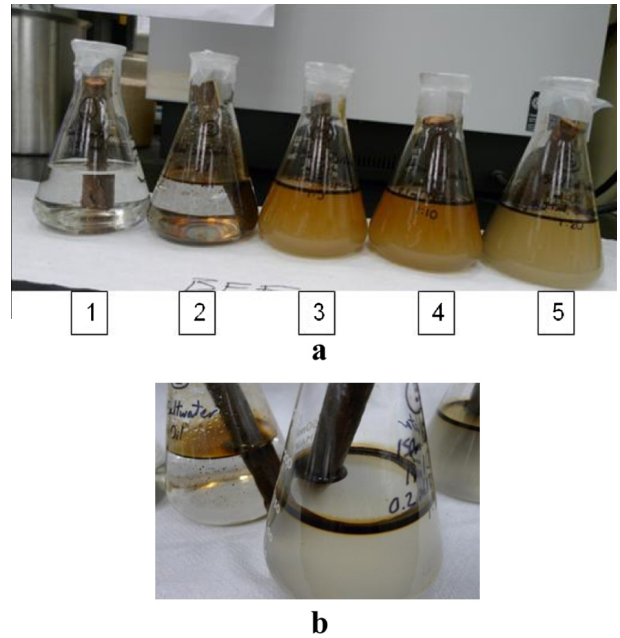

Fig. 1. Root exposure experiments (1: salt water only, 2: salt water and crude oil, 3: salt water, crude oil, dispersant at DOR = 1:5, 4: salt water, crude oil, dispersant at DOR = 1:10, 5: salt water, crude oil, dispersant at DOR = 1:20): a. root samples in salt water solutions, b. oil ring formation around the root in solutions containing floating crude oil (left: saltwater and oil, right: salt water, crude oil, dispersant at DOR = 1:10).

The water flux through the two main root layers (epidermis and endodermis) can be represented by two sequential membranes as presented in Fig. 3. Resistance to water flux due to fouling of the layers can be represented by the resistances-in-series model, with the resistances corresponding to the pore blockage and oil deposition on the root layers.

Normalized time dependent flux through the epidermis can be expressed by the following equation (Tansel et al., 2000):

$$J_{t1}/J_{o1} = 1/(a_1 + b_1 e^{k1t}) \tag{1}$$

$$a_1 + b_1 = 1 \tag{2}$$

where a_1 and b_1 are membrane specific parameters, and k_1 is the fouling rate of epidermis, J_{t1} is the radial water flux at time t, and J_{o1} is the initial flux. Assuming a specific fraction of water that is transported through the epidermis will be transported through the endodermis; the water flux through the endodermis can be expressed as:

$$J_{t2}/J_{o2} = \eta[1/(a_1 + b_1 e^{k1t})][1/(a_2 + b_2 e^{k2t})] \tag{3}$$

$$a_2 + b_2 = 1 \tag{4}$$

where a_2 and b_2 are membrane parameters, and k_2 is the fouling rate of endodermis, η is the fraction of water entering through the epidermis that passes through the endodermis, J_{t2} is the flux at time t, and J_{o2} is the initial flux.

The values of a_1 and a_2 are the resistance parameters of the root layers (epidermis and endodermis) which do not change with time. The values of a_1 and a_2 are typically between 0.10 and 0.30 (Tansel et al., 2000). The coefficients b_1 and b_2 correspond to the time dependent components of the resistances for epidermis and endodermis, respectively. Assuming the values of a and b as 0.15 and