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Review

Toxicities of oils, dispersants and dispersed oils to algae and aquatic plants: Review and database value to resource sustainability

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ABSTRACT

Phytotoxicity results are reviewed for oils, dispersants and dispersed oils. The phytotoxicity database consists largely of results from a patchwork of reactive research conducted after oil spills to marine waters. Toxicity information is available for at least 41 crude oils and 56 dispersants. As many as 107 response parameters have been monitored for 85 species of unicellular and multicellular algae, 28 wetland plants, 13 mangroves and 9 seagrasses. Effect concentrations have varied by as much as six orders of magnitude due to experimental diversity. This diversity restricts phytotoxicity predictions and identification of sensitive species, life stages and response parameters. As a result, evidence-based risk assessments for most aquatic plants and petrochemicals and dispersants are not supported by the current toxicity database. A proactive and experimentally-consistent approach is recommended to provide threshold toxic effect concentrations for sensitive life stages of aquatic plants inhabiting diverse ecosystems.

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1. Introduction

Hydrocarbons in aquatic environments have biogenic, natural geologic and anthropogenic origins such as oil spills, the focus of this review. Although damage may occur from low level continuous discharges to freshwater and saltwater environments, the environmental effects of large oil spills to marine waters have received the most attention by the public and regulatory and scientific communities. The ecological effects of these spills have been the subject of considerable laboratory and field research; however, determinations of phytotoxic concentrations of crude and dispersed oils have been a relatively minor subset of these efforts in recent years and apparently of less interest than determining toxicities for faunal species. Numerous examples of this imbalance exist. In data reviews, bibliographies and scientific presentations less than 10% of entries for toxicity have been for aquatic plants (Wolfe, 1976; National Research Council, 1989, 2005; Gardner et al., 1994; VERTIMAR, 2007). Also, priority lists and recommendations for toxicity assessments (Marine Spill Research Corporation, 1993; National Research Corporation, 2003; U.S. Environmental Protection Agency, 2003; Aurand and Coelho, 2005; Fingas, 2008) and oil toxicity research related to mixtures, biomarkers, and surfactants (Teal and Howarth, 1984; Maddin and Schlumberger, 1991; Fucik et al., 1994; DiToro et al., 2007; Smit et al., 2009) have not considered effects on primary producers. Additionally, phytotoxicity results are not available for dispersants and dispersed oils on the U.S. National Contingency Plan (NCP) Product List Toxicity Summary (U.S. Environmental Protection Agency, 2013a). Whether the apparent lack of consideration for phytotoxicity as suggested above is warranted is addressed in this review.

Aquatic plants are important to the functioning of ecosystems due to their oxygen production, carbon sequestration and their base position in aquatic food chains. Many aquatic vascular plants are considered biological sentinels and keystone species that have a major influence on rates and directions of many community and ecosystem processes. Plant-dominated intertidal and subtidal habitats, often repositories of spilled oil, serve as nursery, feeding and breeding grounds for a variety of faunal and floral species, including recreationally and commercially important fish. The estimated value (USD) of the ecological services per hectare of plant-dominated habitats have been as high as 22,000 (wetlands), 16,750 (mangroves), and 28,000 (seagrasses) (Costanza et al., 1997; Rönnbäck, 1999; Woodward and Wui, 2001; Handley et al., 2007). Despite their value, coverage of these shoreline ecosystems has

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declined considerably across temperate, subtropical and tropical marine areas (Valiela et al., 2001; Walker et al., 2006; Allsopp et al., 2009). Consequently, regulatory agencies and resource managers have focused on their protection with the knowledge that they are often slow to react to and recover from environmental stress such as that caused by oil contamination and associated chemical remediation efforts (Thorhaug 1989; Burns et al., 1993, 1994; Snedaker et al., 1997; Reddy et al., 2002; Culbertson et al., 2008).

The primary objectives of this review are to summarize the reported phytotoxicities of oils, dispersants and their combinations to aquatic plants and to assess the ability of the current database to support toxicity predictions and evidence-based risk assessments. The impetus for the review was the Deepwater Horizon oil spill (2010) which resulted in a large release of oil to the northern Gulf of Mexico. Treatment of the spill and toxicity predictions for the oil, dispersant and dispersed oil on phytoplankton and near-shore plant-dominated habitats was a matter of public, regulatory and scientific discussion with varied conclusions. The lack of a consensus indicated a need for an evaluation of the state-of-the-knowledge for oil and dispersant phytotoxicities. Although previous data summaries are available and a good source for information (e.g. Moore and Dwyer, 1974; Hyland and Schneider, 1979; Miller, 1982; Connell and Miller, 1984; National Research Council, 1989, 2005; Gardner et al., 1994; George-Ares and Clark, 2000), they are scattered throughout the literature and many are dated and limited to specific oils, dispersants and plant species. Therefore, a current and more comprehensive review would be helpful to determine if the toxicity database can support relevant phytotoxicity predictions and risk assessments without additional data generation.

2. Methods

A cross-section of the scientific literature was reviewed for the toxic effects of crude, refined and dispersed oils and dispersants to freshwater and saltwater aquatic plants. However, the review, discussion and recommendations are dominated by information for crude oils and saltwater plants since reported toxicity information for refined oils and more so for freshwater species is limited. Aquatic plants as used in this review represent unicellular and multicellular algae including the cyanobacteria or blue-green algae and vascular emergent and submerged plants. Toxic effects were reviewed for oils applied to waters, substrates and plant tissues. Not included are toxic effects for faunal species dependent on plant-dominated habitats and toxicities of produced waters, drilling fluids, muds and synthetic oils. We reviewed journal articles, literature reviews (e.g. Gardner et al., 1994; Albers, 1998; U.S. Department of Interior 2010), special symposia abstracts and papers (Marine Ecosystem Enclosed Experiments 1987; VERTIMAR, 2007), focused topic journal issues and books (e.g., Kuiper and Van den Brink, 1987; Flaherty, 1989).

Toxicity results from the reviewed reports (most 1970-present) were assumed to be of comparable technical quality but information to support the assumption was not always available. Source of the test species, dilution waters, types of oils and dispersants, oil-dispersant ratios, test concentrations, number of replicates, response parameters, test durations and method of oil application, were required for acceptability. Analytical verification of test concentrations was not required since it has been uncommon particularly for dispersants for which most formulations have been proprietary.

3. Phytotoxicity

It has been known for at least 59 years that crude and refined oils are phytotoxic (Currier and Peoples, 1954; Van Overbeek and Blondeau, 1954). In addition to direct coating and suffocation, oils can cause a variety of sublethal effects on enzyme systems, photosynthesis, respiration, and protein and nucleic acid synthesis. There are no oil-specific standardized phytotoxicity tests designed to determine toxic effect concentrations for the above parameters. However, standard test methods are available for several aquatic plants (Table 1) and non-petroleum contaminants that can be modified for this purpose (Shubert, 1984; Levine, 1984; Sortkjaer, 1984; Gorsuch et al., 1991; Wang, 1992; Brain and Cedergreen, 2009). Despite their availability, these methods have been used infrequently with oils and dispersants. Their lack of use combined with varied plant morphologies (Fig. 1) has resulted in diverse experimental conditions that include differences for test medium preparation, type of media dosed, test durations, test substance application methods, number of test concentrations, test species, life stages, response parameters, effect calculations and dispersant-oil ratios.

Table 1
Examples of aquatic plants recommended for use in standardized toxicity tests published by American Society for Testing and Materials (1993), International Organization for Standardization (1995, 2004), U.S. Environmental Protection Agency (2002 a,b), American Public Health Association et al. (2005) and Organization for Economic Cooperation and Development (2011). Methods described for water and sediment (aqueous extracts, pore water, whole sediment) exposures.

Pseudokirchneriella subcapitata (freshwater green alga)[a]
Desmodesmus subspicatus (freshwater green alga)
Navicula pelliculosa (freshwater pennate diatom)
Anabaena flos-aquae (freshwater blue-green alga/cyanobacterium)
Lemna spp. (freshwater duckweeds)
Myriophyllum sibiricum (freshwater submerged macrophyte
Synechococcus leopoliensis (marine blue-green alga/cyanobacterium)
Skeletonema costatum (marine centric diatom)
Phaeodactylum tricornutum (marine pennate diatom)
Thalassiosira pseudonana (marine centric diatom)
Dunaliella tertiolecta (marine green flagellate)
Gonyaulax polyedra (marine bioluminescent dinoflagellate)
Pyrocystis lunula (marine bioluminescent dinoflagellate)
Champia parvula (marine red macroalga)
Macrocystis pyrifera (marine brown macroalga)
Oryza sativa (wetland, rice)
Scirpus spp. (wetland, bulrush)
Spartina spp. (wetland, cordgrass)

[a] Formerly *Selenastrum capricornutum*.

The frequency of published phytotoxicity studies for oils and dispersants has fluctuated historically. The database consists largely of a series of unrelated research “surges” conducted after major oil spills to marine waters. At least 53 species of marine and freshwater microalgae, 32 macroalgal species, 28 wetland plant species, 13 mangrove species and 9 seagrass species (Table 2) have been exposed to 41 crude oils and 56 dispersants (Table 3) in often single-dose static and static-renewal toxicity tests. Toxicity results for the 135 species are distributed unevenly across different oils and plant types. For example, the database is slanted for information for algae and toxicity data for at least one species in each of four plant categories is available for only three crude oils (Fig. 2). Crude and refined oils have been added to the surfaces of water and soils/sediments, interstitially, and applied to roots, stems and foliage of emergent vascular plants. Weathered crude oils have been recommended for use since this form usually enters shoreline areas (Grant et al., 1993). Likewise, use of water-soluble fractions of oils has been preferred by some since they are relatively simple in composition and are uniformly distributed in the water column. In contrast, use of whole oils has also been recommended (Pulich et al., 1974; Batterton et al., 1978; Gaur and Kumar 1981). Gaur and Singh (1989) recommended that both whole oil and aqueous extracts be used since differences in their toxicities occurred for the cyanobacterium, *Anabaena dolium*.

The goal of most toxicity tests is the establishment of acute and chronic no effect and threshold effect concentrations that can be used alone or as part of species-sensitivity distributions to predict environmental safety of the test compound. These no effect and effect concentrations are the result of multiple-dose toxicity tests which have been infrequently conducted with most aquatic plants. For vascular plants, the number of test concentrations has been usually one or two based on considerations of ease of conductance, economic feasibility and by the usual study objective to determine the effect of an undiluted whole or fractionated oil alone and that of its combination with a dispersant applied at the manufacturers