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Aquatic plants: Test species sensitivity and minimum data requirement evaluations for chemical risk assessments and aquatic life criteria development for the USA☆

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ABSTRACT

Phytotoxicity results from the publicly-available ECOTOX database were summarized for 20 chemicals and 188 aquatic plants to determine species sensitivities and the ability of a species-limited toxicity data set to serve as a surrogate for a larger data set. The lowest effect concentrations reducing the sublethal response parameter of interest by 50% relative to the controls (EC_{50}) usually varied several orders of magnitude for the 119 freshwater and 69 saltwater plants exposed to the same test chemicals. Generally, algae were more sensitive than floating and benthic species but inter-specific differences for EC_{50} values were sometimes considerable within and between phyla and no consistently sensitive species was identified for the morphologically-diverse taxa. Consistent equivalencies of the phytotoxicity databases for freshwater-saltwater plants and floating-benthic macrophyte species were not demonstrated. Two species-sensitivity distribution plots (SSDs) were constructed for each of the 20 chemicals, one based on all available phytotoxicity information (range = 10–76 test species) and another based on information for only five species recommended for pesticide hazard evaluations. HC_5 values (hazardous concentration to 5% of test species) estimated from the two SSDs usually differed four-fold or less for the same chemical. HC_5 values for the five species were often conservative estimates of HC_5 values for the more species-populated data sets. Consequently, the collective response of the five test species shows promise as an interim aquatic plant minimum data requirement for aquatic life criteria development. In contrast, the lowest EC_{50} values for the five species usually were greater than HC_5 values for the same test chemicals, a finding important to criteria-supporting Final Plant Values. The conclusions may differ for comparisons based on other test chemicals, test species, response parameters and calculations.

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1. Introduction

Aquatic plants, broadly defined, undergo chloroxygenic photosynthesis (Bolton 2016). They are a diverse group of freshwater and saltwater species with varied life cycles and architectures. The single cell and multicellular species can be attached, free-floating, submerged or emergent and are represented in the Kingdoms Plantae, Protista, Eubacteria and Chromista. Although their total diversity is unknown, they are numerous. Estimates of algal diversity alone range from 30,000 to 1,000,000 species (Guiry 2012) which includes, among others, as many as 100,000 to 200,000 diatoms (Hawksworth and Kalin-Arroyo, 1995; Guiry, 2012), 10,000 seaweed species (www.seaweed.ie/seaweeds.php) and 2000 to 8000 species of cyanobacteria (Nabout et al., 2013).

It is well known that aquatic plants have ecological and economic value. They serve as the base of most aquatic food chains, provide shelter, stabilize sediment, protect shorelines and act as carbon sinks. In addition, they serve as indicators of water quality and provide filtration and detoxification of anthropogenic chemicals. Marine plants produce 70%–80% of atmospheric oxygen. The economic value of the goods and services produced by coastal shallow -water vegetated ecosystems can be significant (Duarte et al., 2008; Barbier et al., 2011). The many reported global estimates of their annual economic value range between millions to

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trillions USD. For example, the worldwide commercial value of seaweeds for human consumption alone is between $5 and $6 billion/y (www.fao.org/docrep/006/y4765e/y4765e04.htm). In contrast to their benefits, excessive growth from endemic and invasive plant species can impact human health, irrigation, fish and wildlife, recreation and navigation. The estimated cost of controlling invasive plant growth in the U.S. is at least $100 million/y (Pimentel et al., 2005).

The role of aquatic plants for decisions concerning the environmental impact of chemicals has been debated for almost 40 years with no resolution. Understanding the toxicities of anthropogenic chemicals to aquatic plants has been slow to advance and baseline toxicity research has not kept pace with that for aquatic animal toxicity research. Aquatic plants, despite recognition of their toxicological importance since 1967 (USEPA, 1982), have seldom been a determining factor for chemical risk assessments other than for a few agriculture herbicides and marine anti-foulant coatings. They have been of secondary importance to faunal species for regulatory decisions related to, among others, the Clean Water Act (1972), Toxic Substances Control Act (1976), the Comprehensive Environmental Response, Compensation, and Liability Act (1980) and the NPDES permitting process (National Pollutant Discharge Elimination System). This usual minor role is attributable to a faunal-sensitivity bias and to uncertainty concerning which plant species or group of species are chemically sensitive and if their sensitivity is representative of that for the aquatic plant community at large. The faunal bias is due to a lingering assumption, beginning with Kenaga and Moolenar (1979) and reinforced by Stephan et al. (1985), that aquatic plants are generally less sensitive than animal species to chemicals. This assumption has been refuted (Lewis, 1995; Wang and Freemark, 1995; Lytle and Lytle, 2001) but the perception of general insensitivity persists.

Aquatic plants have been an almost non-factor for most National, state and tribal water quality criteria for aquatic life developed during the past 30 years in the U.S. This situation is due, in part, to an absence of clarity for their use in the process. The original methodology (Stephan et al., 1985) includes calculation of an acute criterion which is based on at least one faunal species for at least eight different taxonomic families for acute toxicity and three different families for chronic toxicity. There are no similar specific taxonomic requirements for aquatic plants and acute toxicity (algicidal or phytocidal concentrations). A chronic criterion is also needed for criteria development and it is the most sensitive of either the faunal-based Final Chronic Value (FCV) or the Final Plant Value (FPV). The FPV is the effect concentration resulting from a 96-h toxicity test conducted with an unspecified alga and/or from a chronic test conducted with an unspecified aquatic vascular plant. It is uncertain if the results from one or two phytotoxicity tests is sufficient to represent the sensitivity of the diverse aquatic plant community or if a HC_5 value (hazardous concentration to 5% of test species) from a species sensitivity distribution plot is more appropriate as recommended for aquatic faunal toxicity data. In practice, the FCV is usually the decision calculation due to the limited availability of phytotoxicity information.

The consequences of the secondary role of aquatic plants for most chemical risk assessments and aquatic life criteria are unknown but important to identify to ensure environmental protection for primary producers. One step for reducing uncertainty is identification of either a minimum data requirement (MDR) based on a list of sensitive plant species representing various taxonomic groups or analysis of species sensitivity distributions (SSDs). The primary objective of this report is to provide insight on the value of both options. A subset of the Ecotoxicology Database (ECOTOX; http://cfpub.epa.gov/ecotox/) was summarized to identify sensitive aquatic plant species based on EC_{50} concentrations (concentration reducing the response parameter of interest by 50% relative to the control). In addition, as a technical expansion of Thursby and Lewis (2013), the database was used as a platform to determine the ability of a species-limited data set to serve as a surrogate for larger species-populated data sets based on HC_5 value comparisons.

2. Materials and methods

A brief description of methods follow. More detailed information for species selection, data standardization, statistical procedures, and lognormal probability plots appears in Thursby and Lewis (2015).

2.1. Database selection

The publicly accessible ECOTOX database was the primary source of phytotoxicity information for the review. It is the main source of toxicity information for current U.S. recommended water quality criteria for aquatic life and is a searchable on-line USEPA system that includes information for about 10,300 chemicals and 10,500 aquatic and terrestrial species dating back to 1915. It has minimum data requirements related to the chemical, test species, response parameters, dose, and exposure duration. Toxicity data used from ECOTOX was checked for accuracy against the original citations. Secondary sources of toxicity information included Bao et al. (2011), Chalifour and Juneau (2011), Larras et al. (2012), U.S. Geological Survey, Organization for Economic Cooperation and Development and the USEPA's Office of Pesticide Program's data evaluation records.

The phytotoxicity databases for 38 chemicals were reviewed and those for 20 chemicals, dominated by herbicides and heavy metals, were chosen for analysis (Table 1). The 20 chemicals were selected based on the requirement that toxicity information was needed for at least ten test species of which five species ideally were those recommended for pesticide toxicity screening by the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA). These species are the freshwater green microalga, *Raphidocelis subcapitata* (formerly *Pseudokirchneriella subcapitata* and *Selenastrum capricornutum*), *Anabaena flos-aquae* (freshwater cyanobacterium), *Navicula pelliculosa* (freshwater pennate diatom), *Skeletonema costatum* (saltwater centric diatom) and *Lemna gibba* (floating duckweed). Toxicity information was available for the five species for all test chemicals except for As, Cr, Pb, Ni and Zn for which one (As, Cr), two (Ni, Zn) and three (Pb) substitute species were used. The sequence of substitute selection was a test species from the same genus, and, if not available, then the same order and class. The list of substitutes used for each chemical is available from Thursby and Lewis (2015). Any organisms identified as algae, phytoplankton or other nonspecific identifier were not included. The FIFRA-recommended five species data set was chosen for comparison due to the availability of a relatively large toxicity database derived using standard and widely-used toxicity test protocols (www.epa.gov/test-guidelines-pesticdes-and-toxic-substances/series-850-ecological-effects-test-guidelines).

2.2. Database homogeneity

The ECOTOX phytotoxicity information was screened for experimental consistency prior to use. Toxicity results not expressed as effect (EC_{50}), inhibitory (IC_{50}) and lethal (LC_{50}) concentrations were not used. EC_{50} and IC_{50} concentrations are often used interchangeably in phytotoxicity testing evaluations. LC_{50} values represent the concentration lethal to 50% of the exposed test species. Most results were expressed as an EC_{50} value since many phytotoxicity tests are designed for its calculation and it is the

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