Use of Bioaccumulation Data in Aquatic Life Risk Assessment

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Introduction

Problems of sediment contamination are being viewed increasingly from a risk assessment perspective. Environmental managers with regulatory responsibility for hazardous waste sites, sediment dredging and disposal, and similar problems are beginning to use the tools and approaches of risk assessment to evaluate adverse effects associated with chemical concentrations measured in sediments. In the most general sense, accurate estimation of ecological risks requires both quantification of environmental exposure conditions and understanding of the biological and ecological effects resulting from that exposure. Ecological risk involving chemical stressors is a function of chemical concentration or dose at the site of toxic action (DSTA) and the biological or ecological effects occurring at that chemical concentration. Historically, external exposure has been used in aquatic toxicology as a surrogate for internal dose. Body burden and tissue residue data are thought to provide more direct measures of DSTA. Without complete understanding of the internal dynamics of chemical stressors and their mechanisms of toxic effect, however, these measures are still but estimates (although hopefully improved) of DSTA.

So what, then, are the uses of bioaccumulation and tissue residue data in assessing ecological risk? The value of this kind of information obviously is limited to assessments involving chemical stressors. Further, the data confer insight solely about exposure, just one part of the risk assessment puzzle. Sediment risk assessments in which bioaccumulation is an issue presently focus on the biological responses of individual organisms or their component cells and tissues. However, organismal response can be extrapolated to population-level impacts, and given the appropriate ecological relationships, bioaccumulation can be related to community and ecosystem responses. Assessments involving these levels of ecological organization require trophic transfer models and models involving species interactions.

The objectives of this presentation are threefold: (1) to describe ecological risk assessment and to present EPA's approach for conducting such assessments; (2) to identify how bioaccumulation and tissue residue data are used in each of the steps of ecological risk assessment with respect to aquatic life; and (3) to highlight some of the key uncertainties associated with uses of bioaccumulation data in making risk-based management decisions. Although EPA's framework is by no means the sole approach used to evaluate risks, description of this paradigm will help to illustrate the uses of bioaccumulation data in the various components of any risk assessment. By enumerating uncertainties, I hope to identify general areas of future research that could improve the utility of bioaccumulation information in evaluating the ecological risks of contaminated sediments. Much of the information provided here is obvious; yet it is important to keep these ideas in the forefront of discussions concerning bioaccumulation to ensure that misconceptions are not propagated as part of environmental management and the communication of risks.

Ecological Risk Assessment

Ecological risk assessment can be described as a process for estimating the likelihood of adverse ecological impact resulting from anthropogenic stress. Risk assessments can be retrospective, prospective, or a combination of both. In the context of sediment contamination, retrospective assessments attempt to quantify the impacts of past releases of contaminants on sediment-associated receptors to enhance understanding of current ecological condition. This often is the type of application used when evaluating impacts associated with hazardous waste sites. Prospective assessments involving sediment contamination attempt to predict future impacts based upon the nature and behavior of chemical stressors and potentially exposed ecological systems. Prospective assessments have utility, for example, when selecting among various dredged sediment disposal options. A combination of both retrospective and prospective approaches is useful for evaluating risks of in-place contaminated sediments when both current and future conditions (for example, under various remediation scenarios) are cogent.

Back

As proposed by the U.S. Environmental Protection Agency's Risk Assessment Forum (USEPA, 1992, 1995), ecological risk assessment consists of three primary phases or steps: *Problem Formulation*, *Analysis*, and *Risk Characterization* (Figure 1). Some of the goals of Problem Formulation are (1) to evaluate existing information concerning stressors, receiving ecosystems, and potential ecological effects; (2) to identify assessment endpoints (valued ecological conditions or processes) to be protected; and (3) to develop a conceptual model describing potential risks to assessment endpoints. Discussions among the risk assessors, environmental managers, and other stakeholders are crucial in the process to ensure that the assessment addresses the important regulatory and societal concerns and that the information generated is useful in making environmental management decisions. The Analysis step involves characterization of exposure conditions in time and space, as well as evaluation of ecological effects potentially resulting from those levels of exposure. Analysis involves a variety of empirical and modeling activities, with the ultimate goal of developing profiles of exposure and effect. These profiles are synthesized into estimates of ecological risk during the Risk Characterization step. Characterization activities may be either qualitative or quantitative, and are directed toward providing the information necessary to make informed environmental management decisions. An analysis of the uncertainties associated with the assessment is a critical part of Risk Characterization. EPA's framework is intended to be general with respect to the nature of the stressor(s) and the ecological systems involved in any given assessment. It is therefore useful in assessments involving either chemical or nonchemical stressors, and all types of ecological systems. How bioaccumulation and tissue residue data are used in the specific steps of risk assessment is described in the next three sections.

Uses in the Problem Formulation Phase

Bioaccumulation and tissue residue data play three somewhat related roles in Problem Formulation: (1) to identify those stressors which may impact biological receptors, particularly at higher trophic levels (including humans); (2) to aid in initial descriptions of the potential extent and magnitude of sediment contamination; and (3) to assist in identifying the range of potential biological and ecological effects resulting from exposure. Information concerning important stressors, their concentration distributions, and the effects they potentially elicit supports development of a conceptual model that focuses the remainder of the risk assessment.

Appreciation of bioaccumulation potentials can lead to identification of contaminants that might be available to biological receptors, and may affect organisms at higher trophic levels. The potential for highly lipophilic organic compounds to bioaccumulate, for instance, identifies trophic transfer as an important exposure route when these compounds are present. Not only does this suggest that ecological receptors removed from immediate contact with the sediment should be considered, but it also leads to hypotheses concerning the biological transport of

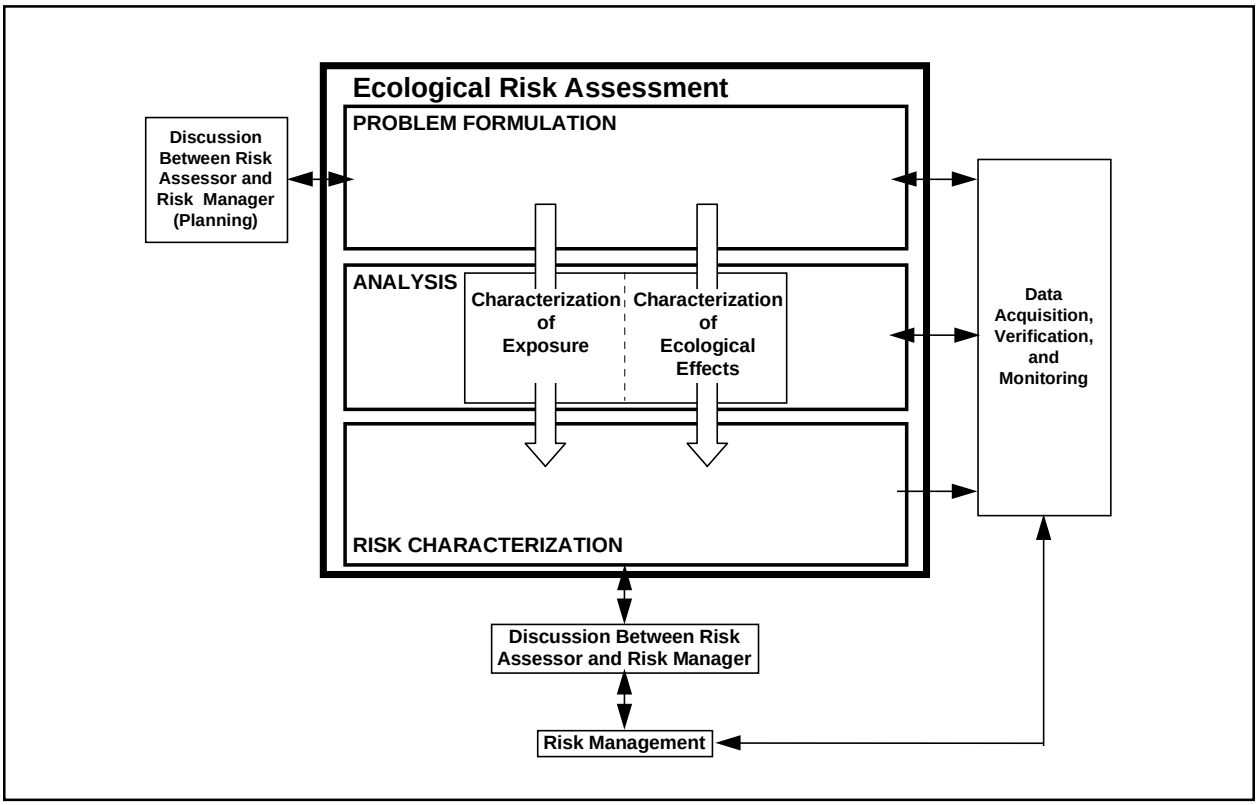

Figure 1. EPA's framework for ecological risk assessment (from USEPA, 1995).

contaminants away from the immediate site of contamination. Conversely, chemicals with low potential to bioaccumulate (some metals, for example) cannot be eliminated as stressors of concern, since the toxic effects of some chemicals are not tightly linked to body burden.

A requirement for adverse impact is the co-occurrence of the stressor with biological receptors. For chemical stressors associated with sediments, environmental exposure (external to biological receptors) is controlled by a number of geochemical factors. Historically, environmental exposure had been quantified as the chemical's bulk concentration in the sediment. Recent advances in understanding the partitioning of chemicals among various environmental phases has enhanced the accuracy of predictions of the availability of chemicals to biological receptors, particularly those in intimate contact with the sediment. In many cases, tissue residue data provide independent verification of these predictions and support description of the extent of contamination. As importantly, tissue residues support evaluation of the extent of exposure to those receptors somewhat removed from direct contact with the sediment. For example, elevated contaminant levels in deployed blue mussels or pelagic finfish indicate contaminant transport from the sediment to the water column or through trophic transfer. This in turn implies that ecological effects may not be limited to benthic organisms.

Knowledge of the degree to which contaminants bioaccumulate, and the tissues in which they accumulate, can provide insight to potential biological effects. PCBs, for example, are known to accumulate in lipid-rich tissues such as gonads and have been associated with reproductive impairment. They also can be transferred during oogenesis to potential offspring, and can cause a number of developmental and survival effects. Thus, in addition to effects resulting from trophic transfer, potential transgenerational effects may be possible.

In combination, the information above can be used to define a conceptual model of exposure leading to potential ecological effects. The conceptual model can incorporate hypotheses of how contaminants move through the physical environment and biotic food webs, thereby identifying key exposure pathways and exposure media for further evaluation. Figure 2 illustrates a generalized conceptual model relating potential contaminant sources in a watershed to ecological receptors in an estuary. In this model, a chemical released to the environment through anthropogenic activity enters the estuary via surface water, ground water, and atmospheric routes. Phase partitioning, water movement, and transport of particulates redistribute the chemical to various environmental compartments (including sediments) within the estuary, leading to potential exposure of a variety of aquatic organisms. Geochemical and biological processes influence uptake of the chemical by biological receptors, which in turn may result in its transfer to organisms at higher trophic levels. In addition to providing a description of environmental exposure pathways (primarily transport and fate), fully developed conceptual models communicate hypotheses concerning the potential adverse effects that may result from exposure. This often requires greater detail in

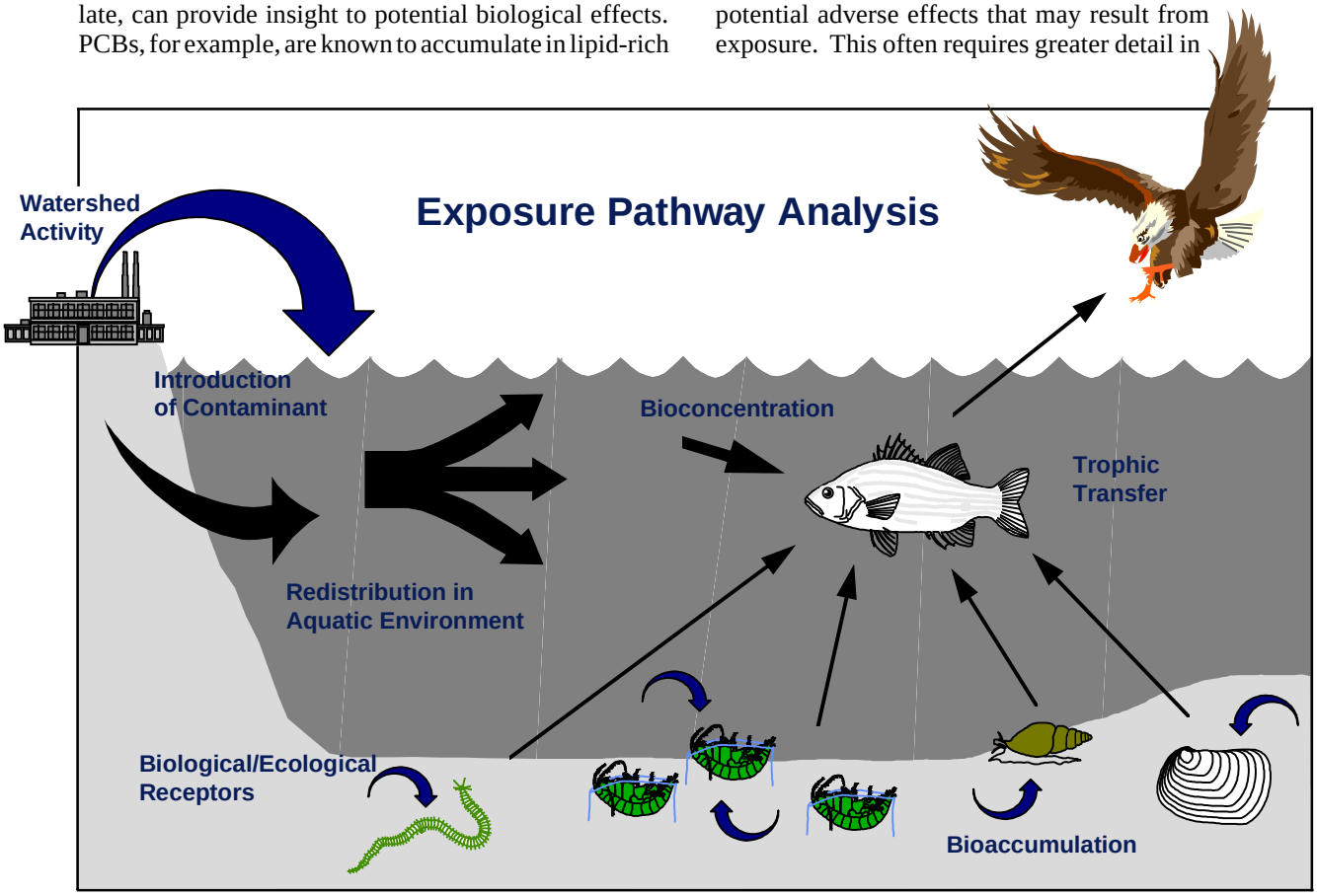

Figure 2. Generalized conceptual model relating contaminant sources to estuarine receptors.

the description of chemical uptake by receptors, and can involve conceptual understanding of the toxicokinetics and toxicodynamics of the contaminant within receptor organisms (Figure 3).

When developed on an assessment-specific basis, the conceptual model can be used to guide the activities in the Analysis phase. For instance, should the chemical of interest be persistent and display a high potential for biological uptake, the conceptual model would dictate analysis of trophic transfer (either empirically or through modeling efforts). Conversely, conceptual models hypothesizing little potential of risk to key consumer organisms, as a result of low bioaccumulation potential or the absence of important trophic pathways, may focus analysis activities on the direct toxicological effects on benthic organisms.

Uses in the Analysis Phase

The Analysis phase of ecological risk assessment involves characterization of exposure and characterization of ecological effects. Legitimately, bioaccumulation data are primarily restricted to evaluations of exposure. Tissue residues can be used, however, as independent variables in models relating exposure to effects.

As discussed previously, bioaccumulation data can help define the availability of chemicals to receptor organisms, improving the accuracy of estimates of exposure over bulk measures made in sediments. For some contaminants, tissue residues can be used to quantify exposure along pathways leading to consumer organisms (including humans). This information is most useful in models of trophic transfer. Residue data also support analysis of the fate of chemical stressors when significant biotransformation or biological transport is possible. These kinds of information support development of a profile describing the nature, extent, and severity of exposure to contaminants found in sediments.

Use of bioaccumulation data to characterize effects in the Analysis step is limited to quantifying internal dose in development of dose-response relationships. These models relate the degree of exposure to levels of biological/ecological response, typically generated through laboratory or field experimentation. Although true DSTA-response models theoretically provide the most accurate predictions of likely biological effect, exposure-response and residue-response models can also be useful. Promising approaches for developing relationships between residues and toxicity have been proposed by McCarty (see McCarty and Mackay, 1993) and others, and several efforts are under way to construct databases containing residue-effects information. Extrapolations to threshold residue values from ambient water quality criteria (Shephard, this conference) and similar toxicity-based benchmarks also hold promise. However, attempts to relate internal dose of chemical stressors to biological effects have met with varying degrees of success.

Bioaccumulation usually is considered a phenomenon relevant to individual organisms, and past assessments of contaminated sediments have tended to focus on effects manifested in individuals (mortality, reproduction, growth, and development). Residue data can also be linked to responses at higher levels of ecological organization. For instance, Munns et al. (1997) used a modeling approach to extrapolate survival and reproductive effects of PCBs on mummichogs (*Fundulus heteroclitus*) to estimates of population growth rate as

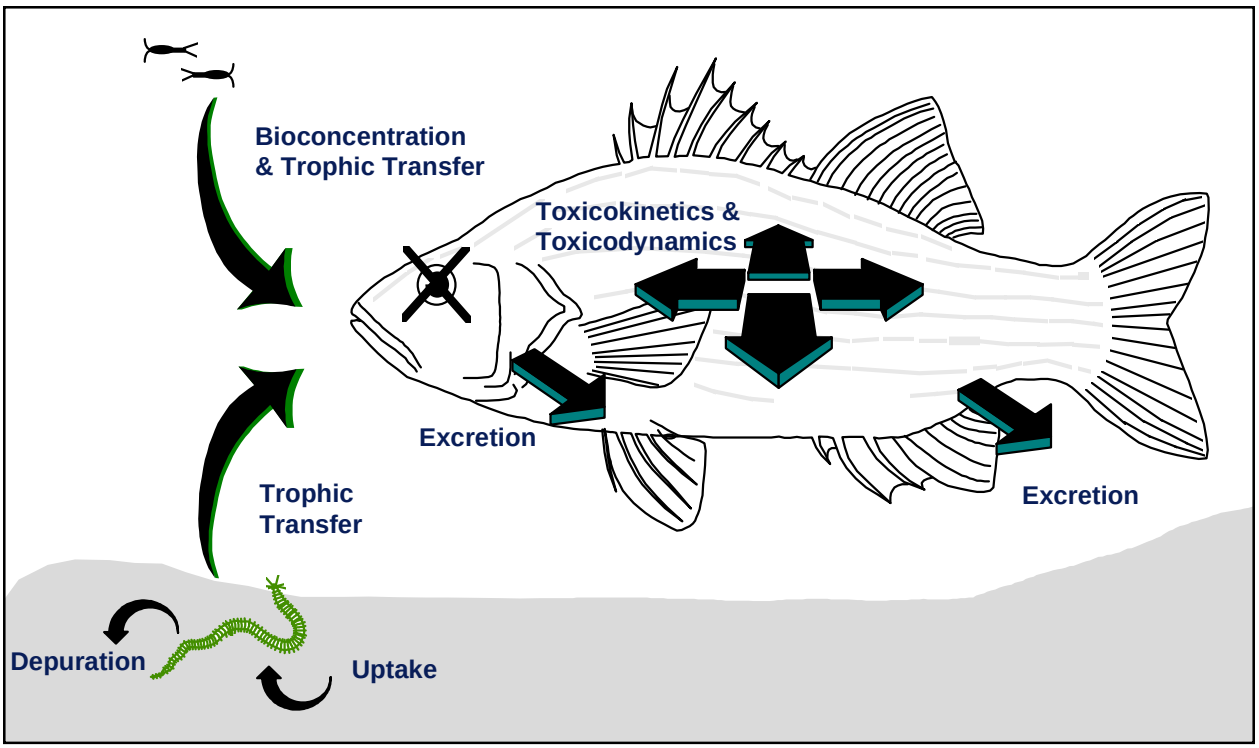

Figure 3. Detail of conceptual model showing contaminant kinetics within an organism.

a function of liver PCB burden (Figure 4). Despite involving many assumptions, such approaches can be subjected to verification through manipulative laboratory and field experimentation. Similar extrapolations can be made to responses manifested at higher levels of ecological organization (for example, shifts in community structure and function mediated by direct toxic effects on individuals and indirect effects resulting from changes in species interactions) by applying ecological models that incorporate residue-response relationships.

Uses in the Risk Characterization Phase

The exposure and ecological effects profiles developed during Analysis ultimately are used to develop understanding of the risks posed by contaminated sediments. The utility of bioaccumulation and tissue residue data in this process therefore plays out directly from the exposure and effects analyses. Similarly, the limitations on their use alluded to above also apply in Risk Characterization.

Both qualitative and quantitative methods have been used to characterize risk. One of the qualitative approaches involves calculation of simple ratios of the environmental exposure concentration (measured or modeled) to biological benchmark concentrations. Biological benchmarks can be receptor-specific toxicity thresholds, sediment quality criteria or standards, or other sediment quality assessment guidelines. Critical body residues or other derived toxicity thresholds based on residue burdens offer a means to incorporate bioaccumulation data into this characterization approach. This so-called risk or hazard quotient approach is most useful in screening-level assessments, since the magnitudes of likely impact are difficult to ascertain from simple ratios. Other qualitative techniques include weight-of-evidence approaches that base conclusions about contaminant-associated risks on the preponderance of information evaluated during the assessment. Residue data are often included as evidence of exposure.

Quantitative characterization methods attempt to provide information concerning the realized or expected severity of impact, often in terms of the probability of a particular level of effect. Dynamic simulation modeling, static assessment, and distributional analysis are examples of techniques providing quantitative estimates of impact. Most complete with respect to analysis of the full range of impact are simulation models that incorporate both direct (toxicity) and indirect (species interactions) responses potentially resulting from contaminant exposure. Trophic transfer submodels are useful in this context when the effects of oral dose can be described. Quantitative techniques are often useful for evaluating the consequences of various remediation alternatives.

Key Uncertainties and Areas for Future Research

As reported during this conference (and elsewhere), our understanding of environmental processes leading to contaminant availability and uptake has improved substantially over the past 5 to 10 years. We have a fairly firm grasp of the sediment factors and partitioning dynamics which influence bioavailability, can model uptake and depuration kinetics with plausible accuracy, and can describe transfer of contaminants from

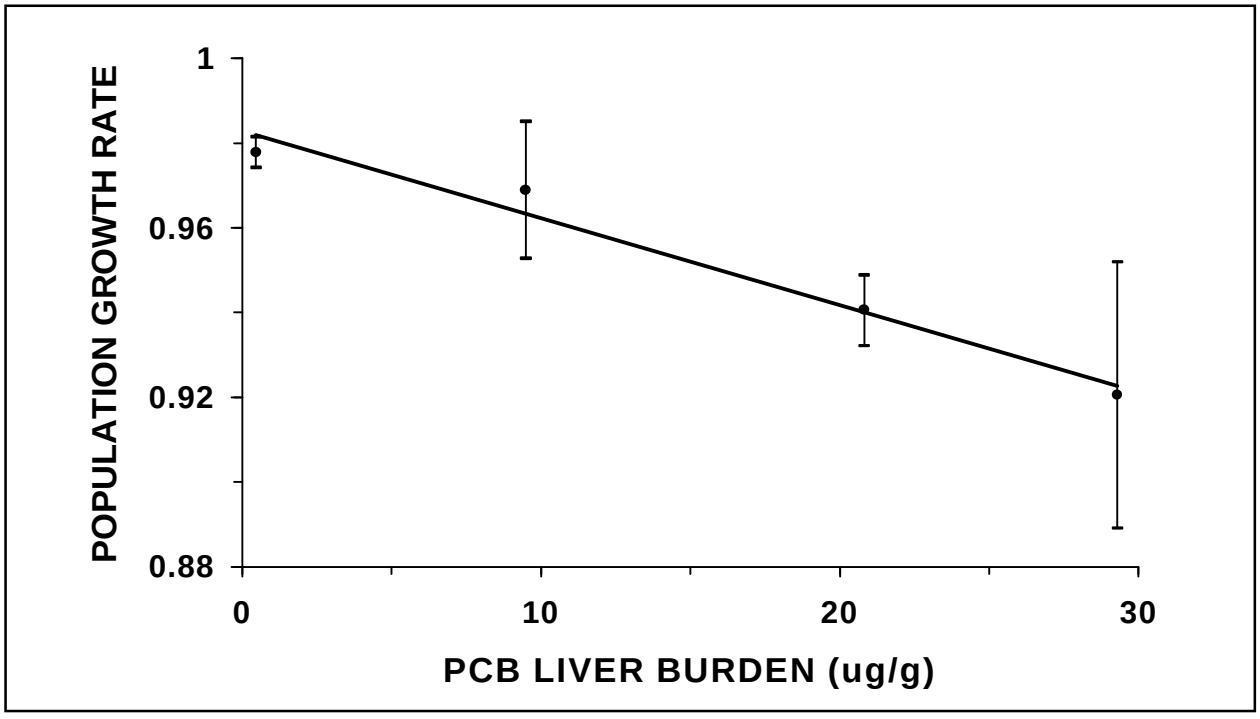

Figure 4. Population-level effects on mummichogs as a function of PCB liver burden (from Munns et al., 1997).

prey to predator with reasonable confidence. Although additional research is still needed in these areas, perhaps the greatest uncertainties associated with the use of bioaccumulation data in risk-based environmental management are associated with linking tissue residues to biological/ecological effect. While advances are being made in this area (for example, the critical body residue and similar empirical approaches), risk assessments will continue to rely primarily on appropriately normalized sediment concentrations as the measure of exposure until this nut is cracked.

In a general sense, factors that hinder our ability to develop residue relationships include: the rates at which contaminants are metabolized or eliminated; the toxicities of intermediate metabolites relative to parent compounds; dose-related induction of enzymatic systems; the modes and time course of toxic action; homeostatic processes resulting in immobilization/sequestration; and the environmental factors that mediate toxic effect. Toxicokinetic and toxicodynamic studies would appear to be fruitful approaches for addressing these issues. These, then, are some of the areas on which future research should focus.

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