

Bioaccumulation in the Ecological Risk Assessment (ERA) Process

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Abstract

Bioaccumulation is a chemical fate and transport process that frequently receives insufficient consideration in the ecological risk assessment (ERA) process. Bioaccumulative chemicals of potential ecological concern (COPECs) require special consideration because they generally have the highest exposure potential, and subsequently risk potential, to upper trophic level organisms. Even though relevant ERA guidance recognizes the importance of including bioaccumulation considerations in the ERA process, there are a number of factors that cannot be adequately addressed in general guidance, or ignored in an ERA. Therefore, the purposes of this paper are to discuss the issues and considerations regarding bioaccumulative, or potentially bioaccumulative, chemicals in the ERA process, and to present recent information relating to such chemicals, so that informed and well-planned risk decisions can be made.

Issue Discussion

1.0 Introduction and Background

Bioaccumulation is an important, although sometimes poorly considered, chemical fate and transport process. When the potential environmental impact of bioaccumulative chemicals to ecological receptors are being evaluated (i.e., for ecological risk assessment), several factors should be considered in order to completely account for overall impacts. Although measures of bioaccumulation are readily available from the scientific literature, and often from field studies, for many chemicals it is difficult to discern actual resulting biological effects in receptors (Shephard 1998). Therefore, some basic bioaccumulation concepts must be understood before one can conduct comprehensive assessments.

1.1 The Bioaccumulation Process

Bioaccumulation is the process by which chemicals are taken up by an organism either directly from exposure to a contaminated medium or by consumption of food containing the chemical. Bioaccumulation can occur in an organism any time a chemical is taken up and stored faster than it is eliminated (i.e., metabolized and/or excreted), and it represents the combined accumulation from diet and direct uptake from abiotic media.

Bioaccumulation is mainly a function of the site-specific bioavailability of a chemical in a particular environmental medium relative to receptor-specific uptake and elimination rates. Bioavailability can be defined as the degree to which a chemical in environmental media can be assimilated, or taken up by, an organism. The degree of a chemical's bioavailability is influenced by factors such as chemical properties (e.g., K_{ow} , solubility, half-life/persistence), the medium or media in which it occurs (e.g., sediment, water, soil), and site-specific factors (such as pH).

1.2 The Biomagnification Process

Among the more important aspects of bioaccumulation is the process of biomagnification. Biomagnification is a special case of bioaccumulation whereby the concentration of a chemical increases at each successive level in the food chain (EXTOXNET 1993). Because an organism at each higher trophic level theoretically consumes many organisms in the level below it, the consumer effectively becomes exposed to the amount of a chemical from all trophic levels below it. Therefore, dietary linkage can allow for chemicals that bioaccumulate in single-celled plants, for example, to reach higher trophic level animal species (e.g., a predatory species such as fox or eagle) at concentrations much higher than in the original environmental medium (e.g., water). It is often the biomagnification of bioaccumulative compounds that is of most concern when conducting ERAs. However, the bioaccumulation of chemicals that do not biomagnify (e.g., selenium) can also be ecologically important.

2.0 Bioaccumulation and ERAs

Because no two sites are alike, it is not possible, nor necessarily desirable, to conduct ERAs for different sites in exactly the same fashion. One of the important early steps in conducting an ERA is to determine which of the chemicals detected on a site are bioaccumulative. Although bioaccumulation is an important process that must be considered as part of an ERA, there is no formal step-by-step guidance for addressing it, and a great deal of professional judgment and informed decision making must be used to ensure that bioaccumulation is adequately addressed. Risk assessors should consider as many site-specific factors, issues, and variables as possible. Regardless of the environmental site setting, the main goal should be to determine the most suitable way to quantify bioaccumulation so that it will be adequately represented when exposure is characterized and ecosystem risk is estimated for a particular site.

2.1 Bioaccumulative or Not Bioaccumulative

Once it has been determined which chemicals are present in each medium at the site being assessed, a decision is needed on the specific methods to be used in the ERA. That decision depends not only on the presence of bioaccumulative chemicals but also on such factors as the presence of sensitive ecological receptors, valued habitats, and complete exposure pathways. The presence of a bioaccumulative chemical in the environment does not prove that there is a resulting ecological risk, but rather suggests that ecological

evaluation of the potential bioaccumulative effects of that chemical is warranted (TNRCC 2000).

Bioaccumulative chemicals are typically evaluated in the ERA for potential effects to upper trophic level species solely on the basis of their presence in one or more on-site media, regardless of the results of any medium-specific comparisons to screening benchmark values. If present, the potential for adverse effects from exposure to bioaccumulative chemicals is evaluated by estimated using food chain models to estimate doses and then comparing these dose estimates to receptor-specific food chain-based benchmarks (e.g., Oak Ridge National Laboratory [ORNL] Toxicological Benchmarks for Wildlife [Sample et al. 1996]). It is usually decided before the ERA which ecological benchmarks will be used for food chain exposure comparisons, and final benchmark values can come from a variety of sources (e.g., regional or federal Environmental Protection Agency [EPA], State, ONRL).

It has been suggested that chemicals displaying a half-life of greater than 30 days (i.e., are persistent), a bioconcentration factor (BCF) of greater than 1000, or a log K_{ow} value of greater than 4.2 tend to bioaccumulate (EPA 2000). Table 1 (Appendix) provides a list of important bioaccumulative compounds that was developed for use in sediment assessments; they exhibit the chemical characteristics mentioned above. Although the list of compounds in Table 1 was developed for sediments, it can serve as a starting point for identifying bioaccumulative chemicals for other media as well. If the information in Table 1 is not adequate, another useful resource for identifying not only the potential for chemicals to bioaccumulate but also for identifying COPECs that are likely to pose substantial risk due to bioaccumulation is Table 3-1 in the Texas Natural Resource Conservation Commission's (TNRCC's), *Guidance for Conducting Ecological Risk Assessments at Remediation Sites in Texas* (2000). The TNRCC synthesized the information available from various sources (e.g., EPA, Environment Canada [EC], United Nations Economic Commission for Europe, ORNL, Bechtel Jacobs Company, etc.) to create its list (see Section 3.1 for resource location).

2.2 Quantifying Site-Specific Bioaccumulation

Once bioaccumulative chemicals have been identified, their concentrations must be measured in ambient media and measured or estimated in relevant organism tissue (usually food of the target receptor). If time and funding allow, and site conditions/exposure potential warrant, site-specific measured tissue concentrations of that chemical should be used for the ERAs so that exposure and effect estimates best reflect site-specific conditions with minimal uncertainty. Because bioaccumulation is such a dynamic process and is influenced by many environmental factors, site-specific data on tissue concentrations in prey items would best represent the actual chemical bioavailability at the site under investigation (Bechtel Jacobs 1998). However, when site-specific data are not available, it is necessary to use uptake models to estimate the uptake of contaminants. These uptake estimates are made with either empirical (e.g. uptake factors, regression) or mechanistic (e.g., physiological, chemical fate and transport) models (Suter et al. 2000).

Bioaccumulation is a nonlinear process; that is, accumulation ratios are generally highest at low concentrations and decrease with increasing media concentrations (Suter et al. 2000). An easy way to illustrate this important principle is to consider ratio-based uptake, or accumulation factors (ACFs), such as bioaccumulation factors (BAFs), bioconcentration factors (BCFs), and biota-sediment accumulation factors (BSAFs). ACFs are commonly used as an index of the extent of bioaccumulation at a particular site because they represent the ratio of the chemical concentration in the organism to the concentration in the environmental medium (i.e., tissue residue divided by the sediment, water, or soil concentration). In some cases, as in BSAFs, these ratios are normalized to site-specific conditions (such as lipid content of the organism). Where site-specific information is lacking, uptake factors are also commonly used to estimate biota concentration when an ACF is available from the scientific literature for a particular chemical and medium. Although many environmental factors influence the degree of bioaccumulation (and the time required to reach a steady-state concentration), conservative (high) ACFs obtained from the literature should be used to estimate concentrations in biota, at least in the initial (screening) steps of an ERA (EPA 1997). Since literature-based ACFs do not account for site-specific factors that can affect bioavailability (and subsequent food chain transfer), use of conservative ACFs can lead to gross over-estimations of biota concentrations and risk estimates (Suter et al. 2000).

Empirically based regression models can offer a much more reliable way to estimate contaminant concentrations in biota (Suter et al. 2000) than ratio-based methods when site-specific measurements are not available. Considerable research has been conducted to support the use of regression models (e.g., Sample et al. 1998a,b; Bechtel Jacobs 1998). Multiple regression models allow for the inclusion of parameters that may affect bioavailability and uptake of contaminants (e.g., pH, organic matter) and take the nonlinearity of the process into account. Regression models can be applied to various sites (i.e., by inputting site-specific values for the variables included in the model), and a better representation of the data variability can lead to a more accurate estimate of COPEC tissue concentrations.

Mechanistic models (e.g., toxicokinetics) offer even more accuracy (i.e., account for more variability) in estimating biota concentrations relative to both ACFs and regression models (Suter et al. 2000). Mechanistic models are based on various aspects of biota physiology (e.g., metabolism, internal mobility, food/contaminant assimilation) and complex chemical properties (e.g., solubility, partitioning coefficients). While these models may provide a much better estimate of bioaccumulation, they are often very complex, requiring data that are rarely available to the risk assessor. Therefore, they are used only under special circumstances.

Given the model tools and principles discussed above, a recommended hierarchy for using bioaccumulation models is as follows (listed most to least preferred):

1. Site-specific log-linear regression (providing there are adequate data),
2. Site-specific ACFs (can be used with less data),

3. Literature-based regression,
4. Literature-based ACFs, and
5. Estimated bioaccumulation based on chemical properties (e.g., log K_{ow}).

If these models do not allow all relevant trophic level prey items to be estimated (for example, result in estimated concentrations in plants and soil invertebrates but not in the birds that feed on them), estimates can be derived using biomagnification factors (BMFs). A BMF is the ratio of the chemical concentration in the tissues of an organism to the tissue concentration in the prey organism from the preceding trophic level. Once an adequate estimate of biota concentrations has been made for all relevant prey items, a risk assessor can characterize exposure, and ultimately risk, to the selected upper trophic level receptors.

3.0 Sources of Information

A number of on-line sources provide information for ERA and bioaccumulation. Links to the resources discussed in this paper are included in this section where possible.

3.1 Ecological Risk Assessment Links

The EPA web site (<http://www.epa.gov/superfund/programs/risk/tooltrad.htm#gp>) is an excellent source of information, including the relevant ERA guidance documents mentioned in this paper.

The ERA guidance provided by the Texas National Resource Conservation Commission (<http://www.tnrcc.state.tx.us/permitting/remed/techsupp/>) is a representative example of state guidance. It also addresses bioaccumulative COPECs.

The ONRL Environmental Science Division (ESD) link for ERA Tools and Applications (<http://www.hsrdrnrl.gov/ecorisk/>) provides access to screening ecological benchmark reports, ORNL-specific ERA guidance documents, examples of completed ERAs, and links to related sites. Further ONRL tools can be found at the Risk Information Web Server (<http://risk.lsd.ornl.gov/homepage/>), including a link to the Risk Assessment Information System, the DOE Center for Risk Excellence Tools, and the EPA Soil Screening Guidance.

3.2 Bioaccumulation Links

The Extension Toxicology Network (EXTOXNET) contains a Toxicology Information Brief on Bioaccumulation (<http://ace.ace.orst.edu/info/extoxnet/tibs/bioaccum.htm>) detailing and discussing many of the general issues and terms used in this paper.

Additional information (such as ORNL-specific guidance documents) on addressing bioaccumulation in the ERA process can also be found through an ORNL ESD link (<http://www.hsrdrnrl.gov/ecorisk/guidance.html>).

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Acronyms

ACF	Accumulation factor
BAF	Bioaccumulation factor
BCF	Bioconcentration factor
BMF	Biomagnification factor
BSAF	Biota-sediment accumulation factor
COPEC	Chemical of potential ecological concern
EC	Environment Canada
EPA	United States Environmental Protection Agency
ERA	Ecological risk assessment
EXTOXNET	Extension Toxicology Network
K_{ow}	Octanol/water partition coefficient
ONRL	Oak Ridge National Laboratory
TNRCC	Texas Natural Resource Conservation Commission

Glossary

Bioaccumulation: The process by which chemicals are taken up by an organism either directly from exposure to a contaminated medium or by consumption of food containing the chemical.

Bioavailability: The degree to which a chemical in environmental media can be assimilated, or taken up by, an organism.

Bioconcentration: The process by which there is a net accumulation of a chemical directly from an exposure medium into an organism.

Biomagnification: The process of bioaccumulation and biotransfer by which tissue concentrations of chemicals in organisms at one trophic level exceed tissue concentrations in organisms at the next lower trophic level in a food chain.

Elimination rate: The time it takes an organism to rid its body of a contaminant or foreign substance; usually through metabolism or excretion.

Environmental medium: Any compartment (e.g., soil, sediment, and water) in which environmental contaminants can accumulate and which receptors can live in or contact.

Receptor: Any organism, population, or community that may become exposed to a stressor.

Stressor: Any physical, chemical, or biological factor in the environment that can induce adverse effects or responses in receptors.

Storage: The temporary deposit of a chemical in a biological tissue or organ; sometimes incorrectly used as a synonym for bioaccumulation.

Uptake: Refers to the entrance of a chemical into an organism (e.g., via inhalation, ingestion, absorption) following exposure; not including the storage, metabolism, or excretion of the organism.

References

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TNRCC (Texas Natural Resource Conservation Commission). 2000. Guidance for Conducting Ecological Risk Assessments at Remediation Sites in Texas.

EPA (U.S. Environmental Protection Agency). 1997. Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conduction Ecological Risk Assessments. Solid Waste and Emergency Response. EPA/540/R-97/006.

EPA (U.S. Environmental Protection Agency). 2000. Bioaccumulation Testing and Interpretation for the Purpose of Sediment Quality Assessment: Status and Needs. Bioaccumulation Analysis Workgroup, Washington D.C. EPA/823/R-00/001.

Appendix

Table 1. Bioaccumulative Compounds of Potential Concern		
Class	Compound	CAS#
Metals and Metallic Compounds	arsenic	7440-38-2
	cadmium	7440-43-9
	chromium VI	7440-47-3
	copper	7440-50-8
	lead	7439-92-1
	methylmercury	22967-92-6
	nickel	7440-02-0
	selenium	7782-49-2
	silver	7440-22-4
	tributyltin (oxide)	56-35-9
	zinc	7440-66-6
Substituted Phenols	pentachlorophenol	87-86-5
	pentachloroanisole	1825-21-4
Low-Molecular-Weight Aromatics	acenaphthylene	208-96-8
	acenaphthene	83-32-9
	anthracene	120-12-7
	fluorene	86-73-7
	phenanthrene	85-01-8
High-Molecular-Weight Aromatics	benzo(a)anthracene	56-55-3
	benzo(a)pyrene	50-32-8
	benzo(b)fluoranthene	205-99-2
	benzo(k)fluoranthene	207-08-9
	benzo(g,h,i)perylene	191-24-2
	chrysene	218-01-9
	dibenzo(a,h)anthracene	53-70-3
	fluoranthene	206-44-0
	indeno(1,2,3-c,d)pyrene	193-39-5
	pyrene	129-00-0
Chlorinated Aromatic Hydrocarbons	1,2-dichlorobenzene	95-50-1
	1,3-dichlorobenzene	541-73-1
	1,4-dichlorobenzene	106-46-7
	hexachlorobenzene (HCB)	118-74-1

Table 1. Bioaccumulative Compounds of Potential Concern		
Class	Compound	CAS#
Chlorinated Aromatic Hydrocarbons (continued)	hexachloroethane	67-72-1
	hexachlorobutadiene	87-68-3
	hexachlorocyclopentadiene	77-47-4
	octachlorostyrene	29082-74-4
	pentachlorobenzene	608-93-5
	1,2,4,5-tetrachlorobenzene	95-94-3
	1,2,3,4-tetrachlorobenzene	634-66-2
	tetrachloroethane	25322-20-7
	1,2,4-trichlorobenzene (TCB)	120-82-1
Halogenated Ethers	4-chlorophenyl phenyl ether	7005-72-3
	4-bromophenyl phenyl ether	101-55-3
Pesticides	aldrin	309-00-2
	chlordane	57-74-9
	chlorpyrifos	2921-88-2
	<i>p,p'</i> -DDD	72-54-8
	<i>p,p'</i> -DDE	72-55-9
	<i>p,p'</i> -DDT	50-29-3
	diazinon	333-41-5
	dicofol	115-32-2
	dieldrin	60-57-1
	disulfoton	298-04-4
	alpha-endosulfan	959-98-8
	beta-endosulfan	33213-65-9
	endrin	72-20-8
	ethion	563-12-2
	ethalfuralin	55283-68-6
	heptachlor	76-44-8
	heptachlor epoxide	1024-57-3
	alpha-hexachlorocyclohexane (a-BHC)	319-84-6
	beta-hexachlorocyclohexane (b-BHC)	319-85-7
	delta-hexachlorocyclohexane (d-BHC)	319-86-8
	gamma-hexachlorocyclohexane (g-BHC, lindane)	58-89-9
	methoxychlor	72-43-5
	mirex	2385-85-5
	nitrofen	1836-75-5
	oxyfluorfen	42874-03-3
	pentachloronitrobenzene (PCNB)	82-68-8
	permethrin	52645-53-1

Table 1. Bioaccumulative Compounds of Potential Concern		
Class	Compound	CAS#
Pesticides (continued)	S-fenvalerate	66230-04-4
	terbufos	13071-79-9
	toxaphene	8001-35-2
	trifluralin	1582-09-8
Dioxins and Furans	2,3,7,8-tetrachlorodibenzo- <i>p</i> -dioxin	1746-01-6
	2,3,7,8-tetrachlorodibenzofuran	51207-31-9
	1,2,3,7,8-pentachlorodibenzo- <i>p</i> -dioxin	40321-76-4
	2,3,4,7,8-pentachlorodibenzofuran	57117-31-4
	1,2,3,7,8-pentachlorodibenzofuran	57117-41-6
	1,2,3,4,7,8-hexachlorodibenzo- <i>p</i> -dioxin	39227-28-6
	1,2,3,6,7,8-hexachlorodibenzo- <i>p</i> -dioxin	57653-85-7
	1,2,3,4,7,8-hexachlorodibenzofuran	70648-26-9
	1,2,3,4,6,7,8-heptachlorodibenzo- <i>p</i> -dioxin	35822-46-9
PCB Mixtures	Aroclor 1016	12674-11-2
	Aroclor 1221	11104-28-2
	Aroclor 1232	11141-16-5
	Aroclor 1242	53469-21-9
	Aroclor 1248	12672-29-6
	Aroclor 1254	11097-69-1
	Aroclor 1260	11096-82-5
	Aroclor 1268	11100-12-4
PCB Congeners	PCB 8 = 2,4'-dichlorobiphenyl	34883-43-7
	PCB 18 = 2,2',5'-trichlorobiphenyl	37680-65-2
	PCB 28 = 2,4,4'-trichlorobiphenyl	7012-37-5
	PCB 44 = 2,2',3,5'-tetrachlorobiphenyl	41464-39-5
	PCB 52 = 2,2',5,5'-tetrachlorobiphenyl	35693-99-3
	PCB 66 = 2,3',4,4'-tetrachlorobiphenyl	32598-10-0
	PCB 77 = 3,3',4,4'-tetrachlorobiphenyl	32589-13-3
	PCB 81 = 3,4,4',5'-tetrachlorobiphenyl	70362-50-4
	PCB 101 = 2,2',4,5,5'-pentachlorobiphenyl	37680-73-2
	PCB 105 = 2,3,3',4,4'-pentachlorobiphenyl	32598-14-4
	PCB 118 = 2,3',4,4',5'-pentachlorobiphenyl	31508-00-6
	PCB 126 = 3,3',4,4',5'-pentachlorobiphenyl	57465-28-8
	PCB 128 = 2,2',3,3',4,4'-hexachlorobiphenyl	38380-07-7
	PCB 138 = 2,2',3,4,4',5'-hexachlorobiphenyl	35065-28-2
	PCB 153 = 2,2',4,4',5,5'-hexachlorobiphenyl	35065-27-1
	PCB 156 = 2,3,3',4,4',5'-hexachlorobiphenyl	38380-08-4

Table 1. Bioaccumulative Compounds of Potential Concern		
Class	Compound	CAS#
PCB Congeners (continued)	PCB 169 = 3,3',4,4',5,5'-hexachlorobiphenyl	32774-16-6
	PCB 170 = 2,2',3,3',4,4',5-heptachlorobiphenyl	35065-30-6
	PCB 180 = 2,2',3,4,4',5,5'-heptachlorobiphenyl	35065-29-3
	PCB 187 = 2,2',3,4',5,5',6-heptachlorobiphenyl	52663-68-0
	PCB 195 = 2,2',3,3',4,4',5,6-octachlorobiphenyl	52663-78-2
	PCB 206 = 2,2',3,3',4,4',5,5',6-nonachlorobiphenyl	40186-72-9
	PCB 209 = 2,2',3,3',4,4',5,5',6,6'-decachlorobiphenyl	2051-24-3
* Recreated from US EPA. 2000. <i>Bioaccumulation Testing and Interpretation for the Purpose of Sediment Quality Assessment: Status and Needs.</i> EPA-823-R-00-001		