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Biological Monitoring: Essential Foundation for Ecological Risk Assessment - DRAFT

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"Risk-based decision making" has become an often-heard buzzword in Congress and government agency circles. The idea implies that policies based on scientific risk assessment--of human health or ecological risks--will be realistic, fair, and cost effective. But for policies developed through risk-based decision making to fulfill this promise, the foundations and endpoints for risk assessment must be properly conceived and relevant for sustaining critical societal needs.

Environments in which living systems cannot sustain themselves cannot support human affairs. We therefore argue that the first, most important step for ecological risk assessment is to set biological endpoints; further, each step in ecological risk assessment should be informed by data from biological monitoring. The measurement endpoints (what is measured) and the assessment endpoints (the ecological goods and services society seeks to protect) must be explicitly biological. Ecological risk assessment will miss its mark if it relies on inappropriate surrogates--such as chemical measures assumed to reflect the health of a biota--or if it is only a veneer, a simple substitution of ecological terminology in another pollution-control or human health risk assessment process.

Risk Assessment

Over the past decade or so, risk assessment has concentrated primarily on human health effects, usually those caused by single toxic substances from single point sources. As practiced since a 1983 report of the National Research Council (NRC, 1983), human health risk assessment asks five questions (van Belle et al., 1996):

- Is there a problem? (hazard identification)
- What is the nature of the problem? (dose-response assessment)
- How many people are affected? (exposure assessment)
- How can we summarize and explain the problem? (risk characterization)
- What can we do about it? (risk management)

Responding to growing interest in specifically ecological risk assessment, EPA in 1992 issued its *Framework for Ecological Risk Assessment* (USEPA, 1992), which was superseded in September 1996 by the *Proposed Guidelines for Ecological Risk Assessment* (USEPA, 1996). In these documents, EPA modifies the human health assessment terminology and process to evaluate "the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors" (USEPA, 1996). The agency's framework asks questions very similar to those asked in human health risk assessment:

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Developing effective multimetric biological indexes involves five major activities:

- Classifying environments to define homogeneous sets within or across regions (e.g., large or small streams, warmwater or coldwater streams).
- Selecting measurable attributes that provide reliable and relevant signals about the biological effects of human activities.
- Developing sampling protocols and designs that ensure that those biological attributes are measured accurately and precisely.
- Defining analytical procedures to extract and understand relevant patterns in the data gathered.
- Communicating the results to citizens and policymakers so that all concerned communities can contribute to environmental policymaking.

Biological monitoring has come a long way over the past century. In aquatic systems, for example, the most pressing concerns at the end of the nineteenth century included the effects of excessive organic effluent on drinking-water quality, the spread of disease, and the status of fish populations. Biotic indexes sensitive to organic effluent and sedimentation were developed to detect and track these threats to aquatic biota (Kolkwitz and Marsson, 1908); this focus continues in modern biotic indexes (Chutter, 1972; Hilsenhoff, 1982; Lenat, 1988, 1993).

With the spread of toxic chemicals throughout aquatic environments, toxicologists began experimentally exposing fish or invertebrates to contaminants. They documented the responses, creating dose-response curves for individual chemical toxicants. The goal was to establish quantitative chemical criteria--surrogate measures that would presumably protect human health or populations of desirable aquatic species by keeping toxic compounds below harmful concentrations. Pollution, primarily from point sources, was controlled by treating wastewater with "best available" or "best practical" technologies (Ward and Loftis, 1989).

But just as biotic indexes measure primarily the effects of organic pollution, chemical criteria based on toxicology apply only to a small number of contaminants. Chemical criteria based on dose-response curves for single toxicants cannot account for cumulative, synergistic, or antagonistic interactions of multiple chemicals in the environment. Moreover, the toxicological approach excludes numerous other threats to the nation's waters, such as the physical destruction of stream channels or wetlands, increasing water withdrawals, the spread of exotic species, and overharvest by sport and commercial fishing.

Over the years, many advocates of biological monitoring have concentrated on abundance, population size, or density of indicator taxa as the biological signal of greatest significance (Green, 1979; Underwood, 1991, 1994; Stewart-Oaten, et al. 1986). But because these biological attributes are notoriously variable even under natural conditions, water-monitoring programs have too often depended on simpler water quality standards based on physical or chemical criteria; biological criteria were dismissed as too complex or not decisive enough.

When ecological research embraced species diversity as a central theme in the 1960s, diversity indexes (e.g., Shannon-Weaver, Morisita, Simpson) came into vogue for evaluating biological communities (Wilhm and Dorris, 1968). Concerns persisted, however, about the properties of these indexes, both statistical (Hurlbert, 1971) and biological (Wolda, 1981; Fausch et al., 1990; Courtemanch, 1996), and few basic or applied ecologists still use these measures. Nevertheless, diversity indexes have left a negative semantic legacy that surfaces whenever the word *index* appears (e.g., see Suter, 1993; Wicklum and Davies 1995).

As environmental awareness grew, new legislation was passed, reflecting broad societal concerns. The

1972 amendments to the Federal Water Pollution Control Act (PL 92-500), now called the Clean Water Act, directly mandated protection of "the physical, chemical, and biological integrity of the nation's waters." Efforts began in 1973 (Karr and Gorman, 1975) to produce a more integrative biological approach to carry out this broad mandate; by 1981 the first multimetric biological index had been developed (Karr, 1981), and the conceptual framework underpinning the approach had been defined (Karr and Dudley, 1981). Yet many water resource managers retained a narrow chemical-contaminant or population perspective.

Through the efforts of many researchers, the index of biological integrity has been improved and effectively adapted for many places around the world (Karr et al., 1986; Ohio EPA, 1988; Plafkin et al., 1989; Oberdorff and Hughes, 1992; Lyons, 1992; Minns et al., 1994; Lyons et al., 1995, 1996; Barbour et al., 1995; Fore et al., 1996; Rossano, 1996). Several state and federal agencies have included multimetric indexes in their biological monitoring programs (Davis and Simon, 1995; Davis et al., 1996).

Among the advantages of multimetric indexes is that they build on the strengths of earlier monitoring approaches (e.g., concepts such as tolerance, richness, ecological guilds, and dose-response curves). They rely on empirical knowledge of how a wide spectrum of biological attributes respond to varying degrees of human influence. In addition, properly constructed multimetric indexes avoid flawed, ambiguous, or difficult-to-use biological attributes, and they are wide in scope (Davis, 1995; Simon and Lyons, 1995).

Building Robust Multimetric Indexes

Indexes of biological integrity, like the multimetric indexes of economic health, integrate multiple attributes of living systems to describe and evaluate a site's condition. Attributes are chosen on the basis of whether they reflect specific and predictable responses of organisms to human activities. Graphs of these attributes against human influence give rise to analogues of toxicological dose-response curves--ecological dose-response curves--where the *y*-axis represents measured values of the attribute, and the *x*-axis measures human influence. Ecological dose-response curves differ in one critical aspect from toxicological dose-response curves. Whereas toxicological dose-response curves usually measure biological response in relation to doses of a single chemical, ecological dose-response curves measure biological response to the cumulative effects of all events and activities within a watershed. The percentage of impervious area in a watershed, for example, reflects, albeit imperfectly, the cumulative impact of point and nonpoint pollution, alteration of drainage networks, channelization of streams, and other human disturbances.

Multimetric indexes are generally dominated by metrics of taxa richness (number of taxa) because a biota's structure, including which taxa are present and their relative abundance, generally changes at lower levels of stress than do ecological processes (Karr et al., 1986; Schindler, 1987, 1990; Howarth, 1991; Karr, 1991). The best, most comprehensive, and accurate multimetric indexes explicitly embrace several attributes of the sampled assemblage, including taxa richness, indicator taxa or guilds (e.g., tolerant and intolerant groups), health of individual organisms, and assessment of processes (e.g., as reflected by trophic structure or reproductive biology).

A multimetric index comprising a suite of such metrics thus integrates information from ecosystem, community, population, and individual levels (Karr, 1981, 1991; Barbour et al., 1995; Gerritsen, 1995). It can be expressed in numbers and words. Rigorously done, multimetric biological monitoring and assessment offer a systematic approach that measures multiple dimensions of biological systems.

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Classifying Environments, Defining Standards

Understanding reference conditions--the baseline against which human effects can be compared--requires distinguishing and classifying ecological systems within and between regions. It also requires defining standards for each of those systems, that is, quantitative benchmarks corresponding to conditions with little or no human influence.

Classifying systems and defining quantitative standards are equivalent to veterinarians' understanding what indicates health in the animal they are treating: healthy for a lizard is not the same as healthy for a dog. Likewise, indicators of ecological health in small midwestern North American streams will not have the same quantitative values as indicators of health in Pacific Northwest streams or large South American rivers. A sample from a healthy 100-meter reach of a small stream in the US Midwest, for example, might contain 30 species of fish; the equivalent sample from a healthy small stream in western Washington State might contain only 6 species.

Knowledge of a site's geophysical setting and undisturbed biological condition--in other words, knowing what produces and constitutes biological integrity for a place--must underpin any biological monitoring effort (Karr et al., 1997).

Choosing Metrics

The effectiveness of biological monitoring programs in assessing ecological risks, and in providing biological criteria that can be used and enforced in management or restoration programs, rests on choosing biological attributes that provide consistent and reliable signals about resource condition. Determining which attributes provide such signals--choosing metrics--is a winnowing process, where each attribute is essentially a hypothesis to be tested and accepted or rejected by asking, Does this attribute vary systematically with varying degrees of human influence?

The choice of attributes and the predictions of how they will vary under human influence are guided initially by ecological principles, theory, and a site's natural history. But successful biological monitoring depends most on demonstrating that an attribute has a reliable empirical relationship--a consistent quantitative change--across a range, or gradient, of human influence. Unfortunately, this crucial step is often omitted in many local, regional, and national programs to develop multimetric indexes. As a result, attributes that are appealing theoretically are sometimes included in indexes before an empirical relationship is shown.

A striking conclusion from 15 years' research and selecting metrics is that the same major attributes give reliable signals of resource condition in different circumstances (Karr 1997a). Across diverse taxa and regions, similar biological attributes (e.g., taxa richness and the relative abundance of tolerant organisms) are consistent and reliable indicators of site condition. As a result, every county or community project need not test and define its own locally applicable metrics. Scientists and resource managers can implement local biological monitoring and assessment programs based on the results of other studies.

Sampling at the Right Scale

Successful biological monitoring programs depend on accurate measures a site's fauna or flora, especially those components influenced most by human disturbance. Thus the spatial and temporal scale of sampling should detect and foster understanding of human influences, not document the magnitude and sources of natural seasonal or successional variation in the same system.

Analyzing Data to Reveal Biological Patterns

Multimetric biological monitoring should combine biological insight with statistical power. Regional biology and natural history--not a search for statistical relationships and significance (Stewart-Oaten, 1996)--should drive both sampling design and analytical protocol. Among the best analytical tools for deciphering relationships between biological attributes and human influence are simple graphs. Graphs reveal, better than strictly statistical tools, patterns of biological response, including "outliers," which may convey unique information that can help diagnose particular problems or traits of a site. Graphical displays illustrate variation in behavior among taxa in response to specific disturbances; they also reveal the direction and magnitude of change, for example, along a longitudinal transect down a stream.

Although statistics can and should be used to validate metric choices and predictions while building a multimetric index, excessive dependence on the outcome of statistical tests can obscure meaningful biological patterns. Too often, a narrow focus on *p*-values rather than on biological consequences limits the value of biological monitoring (Stewart-Oaten et al., 1986, 1992; Stewart-Oaten, 1996). Dependence on narrow statistical approaches overlooks the fact that a statistically significant result (small *p*-value) may not equate with a large important effect, as researchers often assume; similarly, a statistically insignificant effect (large *p*-value) may well be biologically important (Yoccoz, 1991; Stewart-Oaten, 1996).

Communicating So Biological Monitoring Can Be Used

What good is the most rigorous analysis if it cannot be communicated? Communicating the condition of biological systems, and the consequences of human activities to those systems, is the ultimate purpose of biological monitoring. Effective communication can transform biological monitoring from a scientific exercise into an effective tool for environmental decision making. Politics plays an enormous role in environmental policy decisions; how can scientists hope to affect those decisions if they cannot communicate effectively to the decision makers?

Of course biologists must extend what they have learned about monitoring in fresh water to other environments and other taxonomic groups. But they must also avoid gathering and becoming overwhelmed by too much information. Like any scientific method, biological monitoring generates many new and interesting questions, methods, and refinements. But scientists and managers need to realize that they already know enough about how biological systems respond to human influence to make decisions that will halt the decline of our nation's waters. Managers must *use* what they already know.

With multimetric indexes that explain biological condition in numbers and words, biologists can make use of what they know, now. By talking and writing well beyond the confines of academic journals, they can root out the call for more research and call instead for widespread understanding of the real nature of ecological risks. People need, want, and deserve to understand these issues.

Using Biological Monitoring to Compare Places

A robust index of biological integrity is tailored for a particular site. Multimetric biological monitoring accounts for the geographic variation in the chemical, physical, and biological properties underlying the biological conditions at a site. Multimetric indexes thus make it possible to compare sites objectively across geographic regions. Using these explicit cross-region comparisons, citizens and decision makers can better see and understand the consequences of their present and planned land-use activities and thereby set priorities for use, protection, or restoration.

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For example, streams in nearly pristine areas of Grand Teton National Park, Wyoming, had near maximum indexes of biological integrity in one study. Streams with light recreational use in their watersheds (hiking, backpacking) had indexes of biological integrity (41 out of a possible 45) that did not differ significantly from those in pristine areas (44), but places where recreation was heavy were clearly damaged (28). Urban streams in the town of Jackson, Wyoming, had the lowest indexes in the region (21) but not as low as urban streams in Seattle (9) or Japan (9-11) (Karr 1997b).

Assessing Ecological Risks

Biological monitoring is the essential foundation of ecological risk assessment because it measures present *biological* conditions--not just chemical contamination--and provides the means to compare them with the conditions expected in the absence of humans. Biological monitoring helps answer questions such as, Do conditions diverge from integrity, and why? How can we avoid activities that degrade our local waters and landscapes and erode their ability to support life? How can we develop our neighborhoods without permanently losing priceless ecological goods and services? What areas can we restore, and how might we go about it?

To protect society's interests in living systems, we must measure and interpret biological signals. For if we do not understand how biological systems respond--and the consequences of those responses for humans--we cannot understand what is at risk from what human actions. When biological monitoring and assessment are integrated with knowledge of regional human activities, managers, policymakers, and citizens can use this information to decide if measured alterations in biological condition are acceptable and set policies accordingly.

We cannot halt degradation of the nation's ecological resources if we continue to act as if our activities carried no ecological risks (Karr, 1995). By enabling us to identify the biological and ecological consequences of human actions, biological monitoring provides an essential foundation for assessing ecological risks.

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