Biological Monitoring and Environmental Assessment: a Conceptual Framework

JAMES R. KARR
Smithsonian Tropical Research Institute
PO Box 2072
Balboa, Republic of Panama

ABSTRACT / Direct biological monitoring is essential for effective assessment efforts. Past approaches to biomonitoring are too simplistic (for example, toxicity testing, indicator species) or conceptually invalid (diversity indexes). Assessments that use ecological guilds use ecological principles in a more integrative fashion. The best long-term approach is development of suites of metrics, like those used in the index of biotic integrity (IBI), to reflect individual, population, community, and ecosystem attributes in an integrative framework. Efforts to use the conceptual content of IBI in a wider diversity of habitats should be encouraged and followed up with effective control actions.

Both natural events (tornados, tidal waves, volcanic eruptions, and the like) and events precipitated by human activities threaten the health or well-being of human society. We can plan to minimize but cannot prevent the impacts of natural events. Mankind's failure to use ecological principles to minimize negative impacts of human activities is arguably the most important failure of the twentieth century. In an era when mankind's activities are the dominant force influencing biological communities, proper management requires understanding of pattern and process in biological systems and development of assessment and evaluation procedures that assure protection of biological resources. That assessment must include direct biological monitoring.

But the use of direct biological monitoring is often controversial, especially in monitoring and assessment of water resources. Even when the importance of biological monitoring is admitted, selection of a methodology or even a philosophical approach may be difficult. For example, water resource managers have depended on monitoring of physical and chemical parameters as indicators of biological conditions despite the obvious weaknesses of that approach (Karr and Dudley 1981). Some direct approaches for biological monitoring have been developed but a lack of consensus among biologists, fueled by bureaucratic inertia, tends to favor established procedures. Even when biological monitoring is attempted it commonly addresses only toxicity instead of treating the wider array of perturbations from human society that reduce biological integrity. Biotic integrity is "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region" (Karr and Dudley 1981).

KEY WORDS: Biological monitoring; Biotic integrity; Bird communities; Environmental assessments; Fish communities; Guilds; Indicator species; Water resources

My goal in this article is to advocate integrated biological and chemical/physical monitoring. The latter is widely accepted but the insight for environmental decisions from direct biological assessment is generally neglected. To be most effective, biological monitoring should encompass individual (health), population (structure and/or dynamics), community (structure), and ecosystem (function) attributes. My central premises are that (a) biological monitoring is an essential component of all assessment efforts and (b) the biological foundations used in such monitoring must include ecological insight from studies of the structure and dynamics of populations, communities, and ecosystems. Finally, I also point out that proper assessments can only help to pinpoint problems. Control actions are needed to solve problems.

Biomonitoring and the Guild Concept

The most common use of the word *biomonitoring* comes in the context of toxicity testing. This relatively narrow approach concentrates on the effects of various compounds on health and/or survivorship of individual organisms. I do not use *biomonitoring* in that context.

I use it more broadly to evaluate the health of a biological system to assess degradation from any of a variety of impacts of human society (Karr and Dudley 1981, Karr and others 1986). One common, but often flawed, approach is the use of indicator species (Mannan and others 1984, Morrison 1986, Karr and others 1986). For water resource assessments indicator species may be indicative of declining oxygen levels, while in terrestrial environments an indicator species might be a species susceptible to modification in physical habitat (for example, some birds in selectively logged forest). This approach is too simplistic for use

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in comprehensive biomonitoring. Another common approach, use of species diversity indexes, is conceptually invalid. The interdependence of richness and abundance is confused and information on species function is lost altogether (Karr and others 1986).

In contrast, the guild concept (Root 1967) provides a more integrative ecological perspective for environmental assessments. The guild concept in ecology has its origins in population biology and the niche concept (Root 1967). Decisions based on careful application of this concept offer an opportunity to improve environmental assessment (Severinghaus 1981, Landres 1983, Verner 1984). Yet, like any analytical approach, the guild concept has both strengths and weaknesses (Szaro 1986). I illustrate some of the strengths in the following pages with examples drawn from both terrestrial and aquatic ecosystems with which I am personally familiar.

However, I also urge awareness of the weaknesses of simplistic use of the guild concept for decisions about environmental problems. Adoption of guilds as a simplistic reflection of environmental quality could lead to problems similar to those of the 1960s, when there was excessive dependence on a number of quantitative indexes of diversity (such as the Shannon–Wiener function).

Water Resources, Guilds, and Fish Communities

Water resources of North America have been modified by humans since well before Europeans came to the New World. At first, impacts were minor and, in general, had little effects on quality and quantity of water available. As human populations increased, degradation in water resources was more widespread and its causes more complex.

Following passage of clean-water legislation, efforts to improve water resources became less integrative as they concentrated on treatment of chemical contaminants from point and, later, nonpoint sources. While this approach helped to protect water quality, it allowed continuing degradation in a variety of aquatic resources, particularly fishes (Karr and others 1985a).

Indeed, the legislative history of the Clean Water Act, and the implementing regulations precipitated by that act, have been ineffectual because the connections between impacts and causes have been very difficult to quantify and to control. Physical and chemical parameters of water resource systems (for example, dissolved oxygen, nitrogen, phosphorus, and heavy metal content) were used as indicators of biotic integrity, with the assumption that correcting physical/chemical problems would ensure biotic integrity. But chemical monitoring misses many of the human-induced perturbations that impair uses of water (Thurston and others 1979, Karr and Dudley 1981). Habitat alteration, reduced flow, and alteration in energy supplies to support an aquatic community are examples of human impacts that degrade stream communities but that are not detected by physical and chemical monitoring. Direct biological monitoring can detect these impacts. Thus, continuing emphasis on physical/chemical parameters and technology-based approaches to controlling their impacts must be replaced by more direct biological monitoring.

Recent work with fish communities demonstrates the value of including selected ecological classifications (guilds) to analyze degradation in water resource systems. Analysis of changes in fish communities of the Maumee and Illinois Rivers since 1850 shows that a majority (67%) of fish species in the Illinois watershed have declined, with fewer but still a substantial number (44%) having declined in the Maumee River (Karr and others 1985a). Declining populations characterized many species in rivers of all sizes from headwaters to the largest river reaches in each watershed. Headwater regions were most impacted in the Maumee, with a lower percentage of species declining as one moves to larger streams (Figure 1). In contrast, most species in all river size classes had declined in the Illinois River.

Additional analysis using a guild-based approach yielded insights about pattern in fish communities of disturbed areas and processes that produce community pattern. Of the 14 species that declined in the headwater streams of the Maumee River watershed, most depended on invertebrates as their primary food. No omnivores or planktivores declined and only one herbivore declined in the Illinois River (Karr and others 1985a).

An analysis of the human impacts responsible for these alterations in guild patterns shows that a complex of ecological interactions are altered by human activities and many of these affect the guild structure of aquatic communities. For example, alteration of a headwater stream by canalization or clearing of nearstream (riparian) vegetation alters the system's food base and the guild structure of the fish community (Schlosser 1982), changing the community to one dominated by omnivores and herbivore–detritivores. Invertivores and invertivore–piscivores decline sharply.

Channel and riparian alteration also increase sunlight and availability of nutrients, especially in agricultural areas. As a result, late summer algal blooms often choke waterways and, in combination with high water temperatures, stress fish populations. Finally, channel

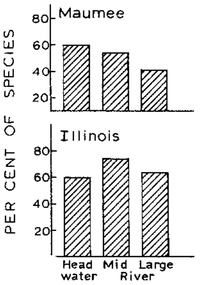

Figure 1. Percentage of species declining or extirpated as a function of river size in the watersheds of the Illinois and Maumee Rivers. Modified from Karr and others (1985a).

activities in headwater streams, in combination with changes in land use, produce more extreme drought and flood conditions (Karr and others 1983).

The guild structure of the community of larger rivers has also been altered by human impacts. Early in this century Chicago diverted its sewage from Lake Michigan, its water source, into the Illinois River. Subsequent increases in toxic effluent and the maintenance of the Illinois as a navigable river have also reduced fish populations through resuspension of a variety of fine particulates that destroy invertebrate communities and thus remove the food base of many fishes (Herricks and Gantzer 1980).

Introduction of an exotic, the carp (*Cyprinus carpio*), also produced major changes in the fish fauna of the Illinois River. A major commercial fishery of native species was replaced by carp, but even populations of this species declined significantly due to the presence of toxic chemicals and habitat alteration. Historically, the Illinois River was the second largest commercial fishery in North America but that commercial fishery has been decimated (Karr and others 1985a).

Why has this degradation of water resources continued and what can be done to reverse the trend? The solution and prevention of environmental problems must be guided by three fundamental principles: (a) the need to preserve human health; (b) the need to preserve aesthetic, recreational, and other uses of biological systems for direct human benefits; and (c), perhaps most important, the need to preserve life support systems that provide both goods and services to human societies through the maintenance of healthy ecosystems. We obviously are very dependent on those systems.

Protection of water resources has been, as noted above, guided by a focus on water quality as a surrogate of biotic integrity in the protection of human health. Lack of integrative consideration of the importance of life-support systems has relegated water-resource systems to continuing degradation, and is likely detrimental to human health as well.

Reversal of this trend depends on incorporation of direct biological monitoring into natural-resource decisions. Recognition of this central problem led me to seek an integrative index that would express the extent of degradation in an aquatic community. Biological communities reflect watershed conditions because they are sensitive to changes in a wide array of environmental factors. Historically, efforts to develop indexes for biological monitoring of water resources used benthic organisms, especially invertebrates and diatoms. But fishes seemed appropriate for monitoring for a variety of reasons:

1) Life history information is extensive for many fish species, especially commercial and sport fishes, and at least some information is available on virtually all North American species.
2) Fish communities generally include species that represent a variety of trophic classes (including omnivores, herbivores, insectivores, planktivores, piscivores). Fish diets often include foods from both terrestrial and aquatic environments. Fish occupy positions throughout the aquatic food web and thus provide an integrative view of the watershed.
3) Relative to diatoms and invertebrates, fishes are easy to identify and technicians require relatively little training. Indeed, most samples can be sorted and identified at the field site with release of study organisms after processing.
4) Evaluation of biotic integrity can be made very rapidly in most cases. No long-term laboratory work, which is often delayed due to other demands, is required. (How many unprocessed invertebrate samples sit on laboratory shelves?)
5) The general public can relate to statements about conditions of the fish community. The results of studies using fishes can be directly related to the aquatic protection mandate of Congress. Monitoring of fishes allows direct assessment of resource potentials that cannot be tested when other taxa are used in a monitoring program.
6) Both acute toxicity (missing taxa) and stress effects (depressed growth and reproductive success) can be evaluated. Comparisons of yearly recruitment and growth dynamics can help to pinpoint unusual stress.
7) Fishes are typically present, even in the smallest streams and in all but the most polluted waters.
8) Population and/or community data on fishes are

already widely collected each year by fish and game departments, university ichthyologists, and others interested in stream biology. Unfortunately, these data bases are often poorly used in the process of environmental quality evaluation. The question then becomes not "Should we collect data on fish?" but rather "How can we improve the quality of fish data we collect and best use those data that are already being collected?"

9) Most fishes reproduce once per year at a set spawning season so that fish populations are relatively stable during the summer, when most sampling activities occur.
10) Fish species are primarily affected by macroenvironmental influences, while algae and invertebrates are more subject to both micro- and macroenvironmental influences.
11) Fishes are relatively long-lived and thereby incorporate temporal integration into assessment of stream conditions.

Thus, I sought a method to assess biotic integrity using fish communities. Such a method should integrate responses of biotic communities through an examination of patterns and processes from population, community, and ecosystem levels—an array of metrics for biology like the leading economic indicators so common in econometric analyses.

Using that approach, I developed an Index of Biotic Integrity (Karr 1981, Fausch and others 1984, Leonard and Orth 1986, Angermeier and Karr 1986, Berkman and others 1986, Karr and others 1986) using data from collections of entire fish communities. Results are summarized as 12 ecological characteristics, or metrics, which can be classified into three major groups: species richness, trophic composition, and fish abundance and condition. The metrics chosen for this analysis are measurable attributes of the community that are correlated with biotic integrity, which is not directly measurable. Several metrics based on the guild concept are integral components of the index of biotic integrity (IBI).

Indeed, one of the strengths of IBI is its multiparameter assessment. The relative sensitivity of the 12 metrics varies with geographic scale considered, type of degradation, and from region to region. No single metric is always a reliable indicator of degradation, but in the aggregate the index based on 12 metrics is strongly correlated with degradation (Angermeier and Karr 1986, Leonard and Orth 1986, Angermeier and Schlosser 1987).

IBI has been used to illustrate degradation in biotic integrity due to a small stream channel reconstruction project (Figure 2) and due to chlorination in secondary treatment (Table 1). Further, addition of tertiary treatment to remove ammonia did not increase biotic integrity (Table 1) above that derived from unchlorinated secondary effluent.

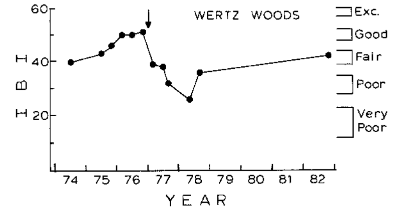

Figure 2. Change in index of biotic integrity (IBI) over time in Wertz Woods, Black Creek, Allen County, Indiana. Note sharp decline in IBI from *good* to below *poor* following Wertz Branch channel work (indicated by *arrow*) late in 1976.

Table 1. Index of Biotic Integrity (IBI ± standard deviation) downstream of wastewater treatment plant during three types of wastewater treatment. Release of chlorinated secondary effluent (phase I), unchlorinated secondary effluent (phase II), and unchlorinated secondary and tertiary nitrification effluent. Modified from Karr and others (1985b).

	IBI values + standard deviation		
Stream	Phase I	Phase II	Phase II
Copper slough	29 ± 8	42 ± 3	40 ± 4
Saline branch	29 ± 3	32 ± 4	33 ± 2
Kaskaskia ditch	33 ± 8	38 ± 3	39 ± 3

The index is now being used successfully by a number of state and federal agencies in water resource assessment and planning. Its broad ecological foundations are a critical component of its value in water resource assessment. Ecologists must develop assessment tools that depend on direct biological monitoring of several metrics, rather than rely on one metric, such as a diversity index, guild structure of the community, or even worse, physical and chemical indicators, which have been very unsatisfactory.

Guilds and Bird Communities

First use of the guild concept in ecological studies (Root 1967) was in an analysis of the niche structure of avian communities. Until 1980 most uses were theoretical or empirical analysis of food or other resource partitioning. Since 1980, the guild concept has been used to evaluate human influences (Severinghaus 1981, Severinghaus and James 1986), especially in the analysis of impacts of forestry practices (Landres 1983, Verner 1984, Mannan and others 1984, Szaro 1986).

The guild concept has been useful, in my experi-

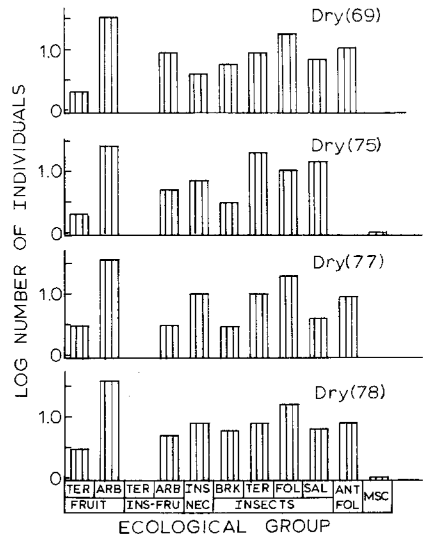

Figure 3. Guild signatures for trophic groups in undergrowth mist-net samples of birds from tropical forest during four dry seasons in central Panama.

ence, in developing ecological and environmental insight. The avifauna of forest undergrowth can be defined, for example, as the birds captured in mist nets operated at heights up to 3 m. Nets are operated for 3 to 6 d until 100 captures are recorded. Each species captured is classified according to its food habits and foraging location. The configuration of the resultant bar graph (Figure 3) is referred to as a *guild signature* (Karr 1980).

Avian guild signatures from forest undergrowth in lowland Panama were strikingly similar over 4 yr. Samples from other regions (Africa, Southeast Asia, and North America) illustrate other patterns and establish standards that vary among region and habitat types (Karr 1980). If a sampled community diverges significantly from that standard, one might then ask: "Why is that the case? Does it result from a human impact, a peculiarity of that environment, or something else?"

Use of guilds as a way of evaluating expectations in certain kinds of communities depends on establishing the baseline structure of these communities and their range of natural variability over time. How do deciduous forests vary in guild structure? How different would coniferous forests and deciduous forest systems be? Can we identify particular characteristics of those different kinds of forest (or other nonforest) ecosystems? How does guild structure change with stress resulting from activities of man? We can use this information to identify potential causes of stress as reflected in a guild signature, and/or we can predict the specific outcome (in terms of the guild structure of the modified community) of certain management regimes. That is, we can use stressed systems to predict outcomes of human activity elsewhere.

Table 2. Comparison of undergrowth avifaunas of two Malaysian forests. Data are based on mist-net samples of birds.

Metric	Bukit Lanjan	Pasoh
Captures	40	36
Species represented	11	15
Capture rate (captures/100 net h)	25	12
Guild structure		
Number of Species		
Insectivore–nectarivore	1	1
Foliage insectivore	9	10
Sallying insectivore	1	4
Number of individuals		
Insectivore–nectarivore	22	3
Foliage insectivore	17	23
Sallying insectivore	1	4

Data collected during 1971 in two forests in Malaysia illustrate this point. The Bukit Lanjan Forest was the site of intensive studies by a variety of biologists, notably mammal specialists, but also plant and bird specialists. In contrast, the Pasoh Forest was relatively undisturbed. Mist-net samples of similar size yielded higher species richness (36%) and lower capture rates (52%) at the less disturbed Pasoh Forest (Table 2). Careful examination of the guild structure of the two communities provides a clearer view of the differences. Similar numbers of species of foliage insectivores and insectivore–nectarivores occur in both areas but the number of captures of insectivore–nectarivores is seven times that caught at the disturbed Bukit Lanjan site. Thus, the Bukit Lanjan site had reduced species richness, low capture rates, and an unusual abundance of one insectivore–nectarivore, a spiderhunter. Apparently, the continuous and regular activity of many research biologists created a variety of openings in the forest undergrowth. Colonizing plants were apparently well adapted to that kind of habitat. And those were the flowering plants that depend greatly on that particular species of bird. Thus, we have a research project designed to understand something about the structure of biological systems but which was so intense that it perturbed the trophic structure of the community.

I concluded that I could not use results of the study at Bukit Lanjan in an analysis of intercontinental variation in avian communities. The coordinators of the long-term research in that area might use these results

Table 3. Primary stratal association for resident land birds in mainland forest near Barro Colorado Island (BCI) and for species on mainland not present (extirpated) from BCI.

	Stratum				
Status	Canopy	Undergrowth	Ground	Bark	Total
All mainland residents	121	76	26	14	237
Extirpated from BCI	11	23	13	3	50
% Extirpated	9.1	30.3	50.0	21.4	21.1
Extirpation relative to expectation	Low	High	High	Equal	—

to reassess their project activities and goals. Their activities were very likely changing the nature—the structural characteristics—of their study communities.

In another area, central Panama, I have been particularly interested in the avifauna of a man-made island in Gatun Lake, a lake created by the damming of the Chagres River to produce the Panama Canal. Although this island is isolated from the nearby mainland by only a few hundred meters, 50 to 60 species of forest birds are missing from it because of its isolation, small geographic extent, and limited availability of sheltered areas along stream channels (Karr 1982a and b). I compared the birds on the island to birds of the nearby mainland forest adjacent to the island, which, in fact, was certainly connected to the island before the canal was created.

Which species are missing from the island, and are they a random selection of species found on the adjacent mainland? With respect to food type, I was unable to reject the random subset hypothesis; that is, the distribution of extinct species among guilds is indistinguishable from the guild distribution on the mainland.

However, when one uses guilds based on where the birds feed in the vegetation column (bark, terrestrial, undergrowth, canopy, and so on), island and mainland distributions of species are significantly different (Table 3). Species on Barro Colorado that are missing tend not to be canopy species. Rather, they tend to be undergrowth species and terrestrial species, but species that glean arthropods from the bark are missing in a proportion which is just about what would be expected at random. Thus, we can look at guilds in several ways, whether we call them guilds or groups. Some ways may and some may not provide us with insight about why, how, and what kinds of species are missing; using only one or another method might prevent us from finding solutions to problems or to understanding why particular patterns exist.

When I realized that primarily undergrowth and ground species were missing, I reexamined the populations of those species. Using eight dry seasons of data, I found that species that are missing from Barro Colorado Island tend to have significantly more variable populations on the mainland than the species still present on the island (Table 4). Therefore, a good predictor of extinction first defines a species as one living in the undergrowth and second as one that tends to have a variable population level. Finally, I have recently been able to show that species with low adult survivorship on the mainland are most likely to be extinct on BCI (Karr, unpublished). As illustrated by this example, creative rearranging of species in guilds can be invaluable in answering special questions about human impact on biological communities. Sole dependence on an indicator species approach would preclude such an analysis.

Table 4. Variability in populations of birds in forest at Limbo Camp, Parque Nacional Soberania, Panama over eight dry seasons. Two groups of species are identified: those still present on Barro Colorado Island (BCI) in Gatun Lake and those no longer present on BCI. Modified from Karr (1982b).

Status on BCI	Number of species[a]	Coefficient of variation of number of captures	
		All species	Insectivores
Present	21 (12)	86.3	93.4
Not present	17 (15)	123.7 $p = .005$	127.8 $p = .005$

[a] All species (insectivorous species).

As a final example of the use of guilds in the study of human impact on bird communities, I draw on work in forest patches isolated in a sea of agricultural land (primarily corn and soybeans) in Illinois. Smaller forest areas support many fewer species than larger areas, much as Barro Colorado Island supported a depauperate avifauna. Forest interior species tend to increase in species richness, and forest edge species tend to decrease in relative importance (Blake and Karr 1984) across the forest size gradient (forest patches of 1 to 600 ha). In addition, guild structure varies with island size, the most notable shift being a decrease in the more opportunistic omnivores as island size increases (Figure 4). Disturbance that creates habitat is-

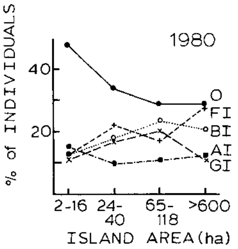

Figure 4. Percentage of individuals in several trophic groups for birds of forest islands of various sizes in east-central Illinois: *O,* omnivores; *FI,* foliage insectivores; *BI,* bark insectivores; *AI,* aerial insectivores; and *GI,* ground insectivores. Modified from Blake (1983).

lands alters the food base in smaller patches much as channelization of streams increased the species richness and abundance of omnivores in headwater streams.

Summary

With these examples I have tried to demonstrate: (a) the value of examining biological communities from the perspective of their ecological organization (guild structure), and, of equal importance, (b) the need for biological assessment to use a broader set of metrics than ecological guilds. Examples using an Index of Biotic Integrity in aquatic communities are especially illustrative of this latter point. Guilds provide an important tool for monitoring, assessing, and evaluating biological systems, especially when coupled with a variety of other ecological insights. In all cases, these biological insights are extremely important for making resource decisions and are more useful than employing narrowly based biological metrics, or worse, evaluations limited to chemical/physical parameters.

With insightful use of our biological knowledge we should ultimately be able to make reliable predictions rather than only after-the-fact judgments. I think some prediction is possible even now; biologists seem hesitant to make predictions, although other disciplines, like economics, regularly produce predictions. I think our track record would be at least as good as those of the economists. In one study, it was shown that the National Bureau of Economics, using the most powerful econometric models and with a massive data base, has failed in 80% of its latest predictions of even the sign of change of the gross national product (*Business Week* 2698:11, 27 July 1982). Surely we can do that well in ecology and we should not apologize if we are not absolutely correct in each prediction. Our reluctance to make predictions in the absence of absolute accuracy contrasts strikingly with the willingness to make predictions within other disciplines. Absolutely reliable prediction in the complicated, dynamic systems studied by ecologists and economists are unlikely but we can, in both disciplines, apply the concept of statistical confidence in combination with biological or economic theory and produce more informed decisions by society. Finally, protection of human health, uses of biological systems for direct human benefits, and the preservation of our planet's life support system can be effective only if integrative monitoring and assessment programs are combined with effective control action and environmental policies.

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