Biological Indicators of Aquatic Ecosystem Stress

edited by S. Marshall Adams

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Symbols and Abbreviations

The following symbols and abbreviations may be found in this book without definition. Also undefined are standard mathematical and statistical symbols given in most dictionaries.

A	ampere
AC	alternating current
Bq	becquerel
C	coulomb
°C	degrees Celsius
cal	calorie
cd	candela
cm	centimeter
Co.	Company
Corp.	Corporation
cov	covariance
DC	direct current; District of Columbia
D	dextro (as a prefix)
d	day
d	dextrorotatory
df	degrees of freedom
dL	deciliter
E	east
E	expected value
e	base of natural logarithm (2.71828...)
e.g.	(exempli gratia) for example
eq	equivalent
et al.	(et alii) and others
etc.	et cetera
eV	electron volt
F	filial generation; Farad
°F	degrees Fahrenheit
fc	footcandle (0.0929 lx)
ft	foot (30.5 cm)
ft^3/s	cubic feet per second (0.0283 m^3/s)
g	gram
G	giga (10^9, as a prefix)
gal	gallon (3.79 L)
Gy	gray
h	hour
ha	hectare (2.47 acres)
hp	horsepower (746 W)
Hz	hertz
in	inch (2.54 cm)
Inc.	Incorporated
i.e.	(id est) that is
IU	international unit
J	joule
K	Kelvin (degrees above absolute zero)
k	kilo (10^3, as a prefix)
kg	kilogram
km	kilometer
l	levorotatory
L	levo (as a prefix)
L	liter (0.264 gal, 1.06 qt)
lb	pound (0.454 kg, 454g)
lm	lumen
log	logarithm
Ltd.	Limited
M	mega (10^6, as a prefix); molar (as a suffix or by itself)
m	meter (as a suffix or by itself); milli (10^{23}, as a prefix)

mi	mile (1.61 km)
min	minute
mol	mole
N	normal (for chemistry); north (for geography); newton
N	sample size
NS	not significant
n	ploidy; nanno (10^{29}, as a prefix)
o	ortho (as a chemical prefix)
oz	ounce (28.4 g)
P	probability
p	para (as a chemical prefix)
p	pico (10^{212}, as a prefix)
Pa	pascal
pH	negative log of hydrogen ion activity
ppm	parts per million
qt	quart (0.946 L)
R	multiple correlation or regression coefficient
r	simple correlation or regression coefficient
rad	radian
S	siemens (for electrical conductance); south (for geography)
SD	standard deviation
SE	standard error
s	second
T	tesla
tris	tris(hydroxymethyl)-aminomethane (a buffer)
U.K	United Kingdom
U.S.	United States (adjective)
USA	United States of America (noun)
V	volt
V, Var	variance (population)
var	variance (sample)
W	watt (for power); west (for geography)
Wb	weber
yd	yard (0.914 m, 91.4 cm)
α	probability of type I error (false rejection of null hypothesis)
β	probability of type II error (false acceptance of null hypothesis)
Ω	ohm
μ	micro (10^{26}, as a prefix)
′	minute (angular)
″	second (angular)
°	degree (temperature as a prefix, angular as a suffix)
%	per cent (per hundred)
‰	per mille (per thousand)

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Biological Indicators of Aquatic Ecosystem Stress: Introduction and Overview

S. Marshall Adams

Introduction

The interest in and use of bioindicators (including biomarkers and biocriteria) for use in environmental assessment has increased steadily during the last decade. Many state agencies in the United States, which function as custodians of water quality management programs under the Federal Clean Water Act (CWA) for example, have incorporated various biological measures into their bioassessment programs to evaluate the quality of surface water resources. Chemical water quality criteria developed through laboratory toxicity tests on standard test organisms have traditionally been used as surrogates for determining attainment of the biologically based goals of the CWA. Chemical criteria were originally developed to set discharge effluent and water quality standards and also to avoid some of the early-recognized problems with measurement of biological parameters in the field, such as those associated with high variability. With a greater variety of biological assessment tools now available, an improved understanding of ecosystem structure and function, and an increased ability to interpret biological data, biocriteria have become more attractive and useful for assessing the effects of environmental stressors on biological systems.

Relying on chemical criteria alone for assessing the status of surface water integrity can, in many instances, inaccurately portray the biological and ecological condition of aquatic systems. For example, impairment, as revealed by use of biological indicators, was evident in 50% of the 645 stream and river segments analyzed in Ohio, whereas no impairments were observed based on chemical indicators (Yoder and Rankin 1998). Use of chemical criteria alone to assess the effects of water quality on ecological systems can lead to an incomplete foundation for legislation related to resource policy because it does not include broader ecological measures (Yoder and Rankin 1998; Barbour et al. 1996). Laboratory-based chemical criteria usually consider only one influential factor (e.g., toxicant) at a time, do not include multiple chemical exposures, and are often restricted to parameters that are convenient to measure. More importantly, however, chemical criteria alone fail to reflect all the other factors in the environment that can impair aquatic ecosystems, such as sedimentation, alterations in habitat and natural flow regimes, varying temperature and oxygen regimes, and changes in ecological factors such as food availability and predator–prey interactions. Biological criteria, on the other hand, possess several attributes that are desirable for assessing the quality of surface water resources. Some types of biocriteria are not only reflective of chemical exposure but also have the capacity to integrate many of the physical, chemical, and biological stressors that operate in aquatic ecosystems. In addition, many biocriteria are capable of integrating the effects of stressors on organisms, both spatially and temporally, and are thus more suited for measuring and interpreting the possible effects of multiple stressors on aquatic ecosystems. Bioindicators, therefore, can reflect environmental problems that might otherwise be missed, or underestimated, by approaches that rely on chemical criteria alone, simply because they provide the opportunity to recognize and account for natural ecological conditions and variability.

Biocriteria can also be used to assess damage or injury to natural resources from environmental stressors. In marine systems, pollution has been defined as "the environmental damage caused by wastes discharged into the sea" (Clark et al. 2001). This definition inherently implies that environmental damage has to be demonstrated in order to prove that a site is polluted. Within this context, chemical criteria and biomarkers of chemical exposure alone cannot be used to assess environmental damage. For example, measuring the levels of a chemical in the environment is basically documenting the level of contamination, while biomarker responses, even though they may provide some indication of damage at the cellular and subcellular level, do not provide assessments of environmental damage at higher levels of biological organization. Biologically relevant endpoints at these higher levels of organization, which are included as a component of the ecological risk assessment process, are typically used as the basis of regulatory and management decisions. In the United States, the Natural Resources Damage Assessment (NRDA) process, which is included under three contemporary environmental statutes (the CWA, the Comprehensive Environmental Response, Compensation and Liability Act, and the Oil Pollution Act), imposes liability for damages to natural resources from release of hazardous substances into the environment. Assessing biological damage or injury requires the use of methods that demonstrate measurable biological responses. Some of the endpoints approved for use within the NRDA process, however, can be characterized as biomarkers (see definition to follow) and, therefore, may not be entirely appropriate for assessing damage at ecological significant levels. Biomarkers at lower levels of biological organization are potentially very useful for assessing stress effects, but they must be correlated and calibrated against higher-level bioindicator responses (Chapter 12). Biomarkers that have been calibrated and correlated with higher-level effects, such as population- and community-level attributes, can indeed serve as valid bioindicators (McCarty and Munkittrick 1996; Adams et al. 2000).

Recognizing the positive attributes of biocriteria and some of the limitations of traditional chemical criteria, the U.S. Environmental Protection Agency (EPA) recently issued technical and programmatic implementation guidance for development of biocriteria in environmental monitoring and assessment programs (U.S. EPA 1996, 1999). The legal authority for developing and providing guidance for biocriteria comes from Section 303(C)(2)(B) of the Clean Water Act (CWA), which requires individual states to adopt these criteria based on bioassessments. In addition, Section 304(a)(8) of the CWA also directs the EPA to develop and publish guidance in the area of biocriteria. Certain biocriteria, such as the Biological Monitoring Working Party (BMWP), are also being applied in the United Kingdom, Australia, and several countries within the European community. This integrative index of benthic invertebrate community integrity (the BMWP) is routinely used along with chemical measures to assess water quality (Hawkes 1998). Therefore, as applied within the environmental management and regulatory framework of these countries, biocriteria can be generally defined as narrative or numeric expressions that describe the reference biological integrity (structure and function) of aquatic communities inhabiting waters of a given designated aquatic life use. Within this definition, then, biocriteria can be generally regarded as regulatory-based measurements and have as their main purpose the documentation of the numbers and kinds of organisms present in an aquatic system.

Because biocriteria, including biomarkers and bioindicators, have become increasingly popular bioassessment tools, it is important to have a comprehensive document that provides guidance relative to the design, measurement, and application of various biocriteria in aquatic ecosystems. The main purpose of this book, therefore, is to provide a comprehensive reference and guide relative to the various biological endpoints that can be measured and used to assess the effects of environmental stressors on aquatic organisms, populations, and communities. The topics addressed by the various chapters in this book are not limited to the strict definition of biocriteria as defined above for regulatory purposes. This book, however, addresses all major levels of biological organization from the biomolecular to the community and landscape levels. Guidance provided by this book can be used in biological monitoring and assessment studies for evaluating the effects of environmental stressors on the integrity of aquatic ecosystems.

Biocriteria, Biomarkers, and Bioindicators

To understand how the various types of biological endpoints addressed in this book can best be applied in field situations, the distinctions between biocriteria, biomarkers, and bioindicators should be clarified. Biocriteria, as defined within the context of regulatory applications, are regarded as the numbers and kinds of organisms present in the aquatic system of interest. This definition or use is generally restricted to measurements and studies at the population and community levels of biological organization and usually includes integrative indices of community health such as the index of biotic integrity (IBI), the stream condition index (SCI), the invertebrate community index (ICI), and the biological monitoring working party score (BMWP).

As applied in this document, biomarkers are considered as functional measures of exposure to environmental stressors, which are usually expressed at the suborganismal level of biological organization (Benson and DiGiulio 1992; Huggett et al. 1992; NRC 1987). Biomarkers, such as molecular, biochemical, and even physiological endpoints, are used primarily to indicate that an organism has been exposed to a stressor such as a xenobiotic chemical. Evidence of biological exposure to a stressor has been more broadly defined by the U.S. EPA (1991) as those endpoints that measure the apparent effects of stressors, including chemical water quality criteria, whole effluent toxicity tests, tissue residues, and biomarkers. Thus, in addition to the more traditional measures of exposure (e.g., chemical tissue residues, acute and chronic toxicity tests), biomarkers are also regarded here as measures of exposure. Bioindicators, on the other hand, are defined less precisely than biomarkers and can be viewed as either structural entities, such as sentinel species (Van Gestel and Van Brummelen 1996), or they can be considered functionally as biological effects endpoints at higher levels of organization (Adams 1990a; Engle and Vaughan 1996). Within this context, then, some bioindicators are included within the definition of biocriteria because bioindicators also include population- and community-level attributes in addition to organism-level and ecosystem- and landscape-level responses. As used by the U.S. EPA (1991) in the Environmental Monitoring and Assessment Program, response indicators are considered surrogates for bioindicators and are operationally defined as composite measures of the cumulative effects of stress and exposure and also include the more direct measures of community and population responses. The main features of biomarkers and bioindicators may be reflected in a single definition that considers a bioindicator as "an anthropogenically induced variation in biochemical, physiological, or ecological components or processes, structures, or functions that has been either statistically correlated or causally linked, in at least a semiquantitative manner, to biological effects at one or more of the organism, population, community, or ecosystem levels of biological organization" (McCarty and Munkittrick 1996). Thus, a biomarker may be operationally considered a bioindicator or even a biocriteria if it can be causally related or linked to a biologically significant endpoint at the organism level or above (Adams et al. 2001).

Biomarkers and bioindicators have their own unique set of advantages and limitations relative to their value and use for assessing the effects of stress on aquatic ecosystems. Table 1 summarizes the major features of biomarkers and bioindicators relative to their advantages and limitations for use in field bioassessment studies. In general, biomarkers are used to indicate exposure of an organism to a stressor, and bioindicators are used primarily as indicators of stress effects at higher levels of organization mainly because of their composite or integrative nature. The main attributes of biomarkers and bioindicators that are important for consideration in the design of bioassessment studies are sensitivity and specificity to stressors, relationship to cause, response variability, temporal scales of response, and ecological or biological significance (Table 1). In general, biomarkers are stressor sensitive and rapidly responding endpoints that help to identify the mechanistic basis of causal relationships between a stressor and its effect. The primary limitations of biomarkers, however, are that they are generally characterized by a relative high response variability (i.e., coefficient of variation is relatively high because response parameters of individuals are typically more variable compared with the more integrative attributes of communities such as diversity, for example), rarely integrate effects of stressors over long periods of time and, most importantly, generally have low ecological relevance. On the other hand, bioindicators, including traditional biocriteria, provide little useful information for helping to understand the underlying causal mechanisms between stressors and effects because their sensitivity and specificity to stressors is low and they tend to integrate the effects of multiple stressors over large spatial and temporal scales (Adams 1990a;

Table 1. Major features of biomarkers and bioindicators relative to their advantages and limitations for use in field bioassessment studies.

Major features	Biomarkers	Bioindicators
Types of response	Subcellular, cellular	Individual through community
Primary indicators of	Exposure	Effects
Sensitivity to stressors	High	Low
Relationship to cause	High	Low
Response variability	High	Low–moderate
Specificity to stressors	Moderate–high	Low
Time scale of response	Short	Long
Ecological relevance	Low	High

Depledge and Fossi 1994). Although bioindicators (and biocriteria) have a relatively low degree of response variability and high ecological relevance or significance, they have little value in helping to identify the underlying cause of observed changes in ecosystems. Thus, when designing and conducting field bioassessment programs, a variety of endpoints should be used that represent a range of spatial and temporal response scales and also include a large range of spatial and temporal sensitivities and specificities to different stressors. The complexity of natural systems, their inherent high variability, and the influence of multiple environmental factors (or stressors) on ecosystems suggest that no single measure (or perhaps even a few measures) is adequate for assessing the effects of multiple stressors on the status or integrity of aquatic ecosystems. An appropriate suite of endpoints is required for determining the biological significance of stress and understanding the underlying cause or mechanistic basis of observed effects (Hodson 1990; Attrill and Depledge 1997). In many instances, simply documenting that a change has occurred in a system or measuring such a change with a few biological parameters may not be adequate. It is also necessary to understand the mechanistic basis of an effect or change if more informed decisions are to be made regarding effective management and mitigation practices in disturbed ecosystems. Overreliance on any one or a few indicators can result in environmental regulation that is less accurate and either under- or overprotective of water resources (Yoder and Rankin 1998). A credible and genuinely cost-effective approach to water quality management should, therefore, include an appropriate mix of chemical, physical, and biological indicators, with each being used in their respective roles as environmental stressor (i.e., contaminant, eutrophication), exposure response (i.e., biomarkers), and effects response (i.e., bioindicators).

The concept of applying a suite of endpoints in bioassessment studies is illustrated in Figure 1, which shows that a combination of both rapidly responding and sensitive biomarkers and the more ecological relevant bioindicators (including biocriteria) should be incorporated in field bioassessment designs. This figure also illustrates that given limited resources (finances and personnel, etc.) for conducting bioassesment studies, the number and types of measurements that can be taken is limited and those responses that are measured should perhaps focus at the organismal level. In addition to an emphasis at the organismal level, study designs should also include a few measures at both the lower levels (i.e., biomarkers) and higher levels (i.e., bioindicators, biocriteria) of biological organization. With such a design, organism-level responses can serve as an intermediate or pivotal response point by which the mechanistic basis of effects at lower levels (biomarkers) can be causally linked to ecologically relevant measures at the population and community levels (bioindicators/biocriteria). This concept of causal relationships between levels of organization is also shown in Figure 2, where increasing levels of biological organization result in decreasing mecha-

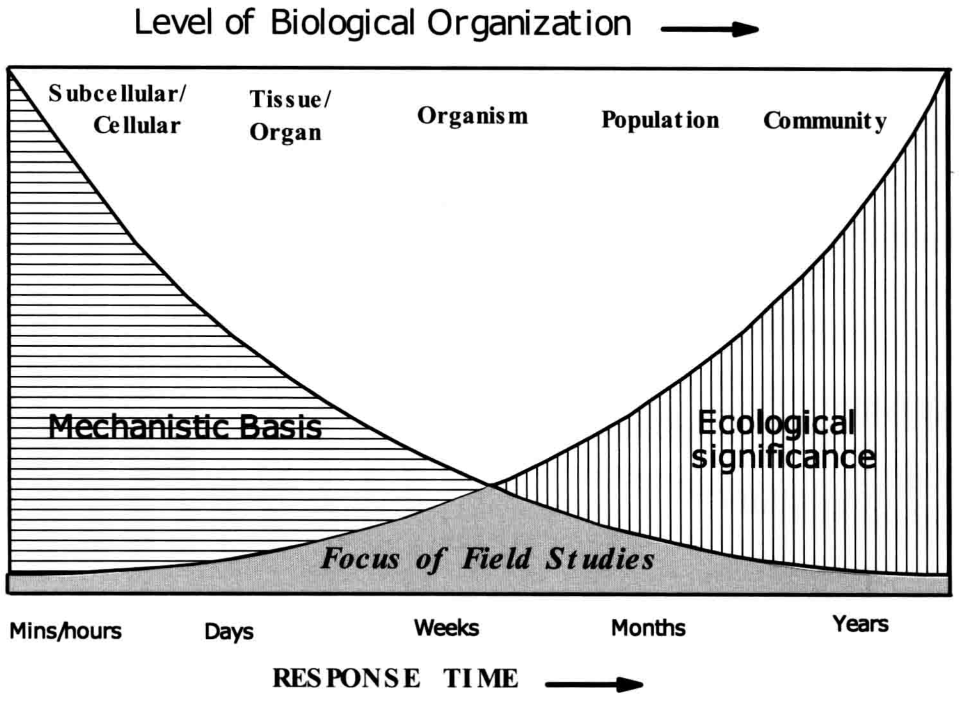

Figure 1. Field bioassessment studies should include a combination of both rapidly responding sensitive biomarkers and the more ecologically relevant bioindicators with a focus at the individual organism level. Organism-level responses provide a pivotal point through which mechanistic understanding and the ecological consequences of stressors can be linked.

nistic understanding but increasing levels of ecological significance. Thus, a selected suite of measures along this continuum of levels of organization is recommended in the design of aquatic ecosystem bioassessment studies.

Scope of Book

Given the above background, the primary purpose of this book is to provide practical information and guidance for improving our ability to assess and predict the effects of environmental stressors on the integrity of aquatic ecosystems. Even though the title of this book focuses on bioindicators, within the strict definition of terms, both biomarkers and bioindicators are addressed by their respective topics within the various chapters of this book. For example, Chapter 2 addresses molecular endpoints that, within their stricter definition, are biomarkers, but molecular responses may also function as bioindicators within the context of using an integrated suite of responses over several levels of biological organization to establish possible causality. For the purpose of this discussion and within the context of this book, there-