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CONNECTING ECOLOGICAL MONITORING AND ECOLOGICAL INDICATORS: A REVIEW OF THE LITERATURE

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ABSTRACT

Ecological monitoring is receiving renewed interest, is being performed with increased scientific rigor, and offers plentiful research opportunities. In the 1990s several countries are embarking on ambitious national ecological monitoring programs as monitoring is becoming more important for assessing ecological status and for underpinning environmental policy decisions and funding priorities. Several important facets of monitoring are reviewed in this article including: 1) the philosophy and objectives upon which monitoring programs are based, 2) the use of ecological indicators for assessing the status of the environment and, 3) criteria upon which to base the choice of indicators. The most important issues in monitoring lie not in post-monitoring data analyses but rather in all phases of the design of the monitoring regime.

BACKGROUND

Recent ecological studies have examined anthropogenic stresses on a regional scale and assessments of ecological conditions [1-6]. Many countries are developing national-scale environmental monitoring programs, including Canada [7], the United States [8], Sweden [9], The Netherlands [10], the United Kingdom [11], the Czech Republic [12], Estonia [13], and the Slovak Republic [14]. Monitoring is designated as one of the top environmental research and development priorities by the U.S. National Research Council [15]. The U.S. Environmental Protection Agency's (EPA) Environmental Assessment and Monitoring Program (EMAP), has defined among its goals to confirm that the nation's

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environmental protection efforts are truly maintaining or improving environmental quality [2, 8]. The judicious selection of ecological indicators for monitoring and reporting is vital to meeting the EMAP goal of developing scientific understanding that can translate environmental monitoring data expressed in several spatial and temporal scales into assessments of ecological condition, and into forecasts of future risks to sustainability of natural resources. Three components of this approach include: 1) intensive long-term research sites, 2) ecological indicators and, 3) multi-tier monitoring design [16].

The EPA has initiated a new, "top-down" approach to ecological risk management, which focuses on larger geographic scales and higher levels of biological organization. Past approaches to risk assessment have traditionally involved single-species toxicity tests and media-specific exposure models and are often performed at local scales [17]. EMAP's monitoring of the status and trends in the condition of representative ecosystems is to serve as the foundation of EPA's Ecological Risk Assessment Program. EMAP will develop and use biological response indicators primarily to assess ecological conditions, and will also measure indicators of contaminant or stress exposure to identify relationships between changes in response indicators and changing stresses on ecosystems over time. Habitat indicators (e.g., salinity, sediment type, vertical vegetation composition, snags, etc.) will be measured to account for natural variations in biological response indicators [17]. Table 1 lists examples of regional, large-scale and long-term monitoring programs in North America and Europe.

This article reviews the general literature base of ecological monitoring, and issues regarding the use of indicators in monitoring. Through the 1970s, the application of the concept of indicators of environmental condition generally focused upon organisms as specific indicators of air pollution/quality, water pollution/quality, etc. [18-19]. This type of indicator is still an integral part of applied ecology and environmental assessment [20]. This article, however, focuses on the literature that addresses general indicators of ecological condition and issues surrounding broad-scale environmental and ecosystem monitoring; it is not a comprehensive review of references on every biological indicator used in pollutant accumulation studies or in the context of a particular cellular or physiological response. It is also not a review of wetland indicators, forest indicators, agroecosystem indicators, etc.; the eight EMAP Ecological Resource Groups (agricultural ecosystems, arid ecosystems, forests, integrated landscapes, near-coastal waters, the Great Lakes, inland surface waters, and wetlands) are tracking the specific literature on individual indicators and monitoring techniques of interest to their respective resources. For more detailed references on indicators considered for use in specific resource classes, see [2]. Additional sources of information on indicators and monitoring strategies are in an "indicator development strategy" [21] and in published reports and articles by the individual EMAP resource groups [22-32].

OTHER REVIEWS

Other reviews related to the subject of ecological monitoring and indicators have been performed. In a background report for the Canadian State of the Environment Program, Sheehy [33] provides an annotated bibliography on forty-five indicators in six areas: quality of life indicators, environmental indices, environmental quality profiles, biological indicators, chemical indicators, and urban environmental indicators. A review of this literature is synthesized into a discussion on requirements of good indicators, problems and limitations in development and application, and what is needed to improve the art of indicator development. Rajagopal and others [34] present a review and database of literature on information integration related to environmental monitoring and assessment. "Indicators" is one subtopic covered within four broad areas: institutional issues, resource/ecological issues, design issues (mathematical/statistical), and technological issues (computer, GIS, remote sensing, and others). They point out that although there are many extensive databases on topics such as water, air, soils, forests, wetlands, biodiversity, agricultural productivity, and land use, much of the data in these data banks has come from many different surveys, networks, and programs of the past several decades. Most likely, these may be difficult to tie together or compare. Spellerberg [35] also notes that many different resource management agencies have different methods, measurements, and objectives, which may make merging of data on larger areas or for longer time frames quite difficult.

In an extensive review of environmental monitoring for parks and other protected areas, Slocombe [36] discusses indicators in the context of environmental monitoring and the analysis of ecosystem stress/response while providing a lengthy reference list with particular depth on Canadian environmental monitoring schemes. The author also touches on the concept of what constitutes ecosystem integrity. Bruns et al. [37] review environmental monitoring in the context of reporting environmental impact assessment for the U.S. National Environmental Policy Act (NEPA). In his review of twenty-one pieces of literature, he discusses monitoring, assessment parameters, and the concept of measuring ecological health. An excellent source of information on indicators with particular relevance to EMAP and regional and national monitoring schemes can be found in the proceedings of an international symposium on ecological indicators [38]. Another recent conference proceedings covers a broad range of the issues concerning regional scale monitoring and ecosystem health [39]. Cairns et al. [40] offer an in-depth discussion of a framework for developing indicators, the purpose of which is to provide for defensible selection of indicators of ecological health in the context of a long-term monitoring program. Originally developed for specific application to the assessment of the Great Lakes system, it provides useful generic information on selecting indicators of ecological condition. Griffith and Hunsaker [41] provide an annotated bibliography of over 500 citations on monitoring, ecological indicators, and ecological health.

MONITORING: PHILOSOPHY, PRINCIPLES, AND DESIGN

Monitoring is the repeated inventory of an item to determine trend and status [42]. Basic reasons to initiate monitoring are: 1) to determine the present and future health of ecosystems, 2) to establish empirical limits of variation in natural resources, 3) to diagnose abnormal conditions and identify issues in time to develop effective mitigation and, 4) to identify potential agents of abnormal change [43]. Among the first steps in implementing this design is deriving a conceptual model of the ecosystem(s) being monitored. This will take the form of: 1) an exhaustive list of mutually exclusive components and descriptions of their relationships and, 2) decisions on the representative elements selected and tested for monitoring. Roux et al. [44] echo some of EMAP's goals for assessing regional aquatic systems as they relate to Australia and illustrate the need for long-term and large-scale monitoring. Currently, the status of aquatic environments in Australia is not well-known, making it difficult to assess extent of any alterations and rate at which changes are occurring. Comprehensive monitoring and assessment programs will establish initial baselines of chemical, physical, and biological resources statistics [45-46]. Still others propose that new assessment concepts are needed for evaluating rangelands status. The current range condition assessments do not inform managers and the public of what they want to know, including status of indicators of biodiversity, erosion potential, nutrient cycling, value for wildlife species, and productivity [47-49].

The U.S. National Research Council [50] has also recommended conducting comprehensive monitoring of regional and national ecological status and trends and strengthening the role of monitoring in environmental management. The Council determined that monitoring meets many needs including: 1) providing information needed to evaluate pollution abatement problems, 2) serving as early-warning systems that permit lower-cost solutions to environmental problems, 3) contributing to knowledge of ecosystems and how they are affected by human activity, 4) providing essential data for the construction, adjustment, and verification of quantitative predictive models, which are an important basis for evaluating, developing, and selecting environmental management strategies and, 5) providing environmental managers the scientific rationale for setting environmental quality standards. Therefore, assessment of the current state of the environment is a prerequisite for rational environmental care [51]. In current global work in ecological restoration of damaged areas, we must thus become more involved not only in management and mitigation, but also in monitoring [52-53]. Simply stated, good management requires good information [54]. The importance of monitoring in establishing policy is noted by Belsky [55].

The philosophy and objectives upon which a monitoring program is based are critical to the success of the program and are mentioned frequently in the literature [56-62, 25]. The lack of well-defined objectives will be fatal to most monitoring programs [63], and the first step in the development of an inventory and monitoring program should be the establishment of a scientifically valid foundation [42]. This critical nature of well-defined objectives is underscored if one believes Tilman's figure (cited in [64]) of only 1.7 percent of "continuous" ecological studies lasting at least five years. Table 1 lists examples of long-term and large-scale monitoring programs in North American, European and international agencies.

Bernstein [65] states that objectives are important both managerially and technically. With respect to regional-level monitoring, he states objectives are important for: 1) integrating scientific knowledge and understanding about a range of resources and impacts, 2) understanding how management and monitoring systems work at both point source and regional levels and, 3) coordinating scientific knowledge, public concerns, and management information needs to develop clear objectives that can guide the design of monitoring programs. He also provides a framework for incorporating the practical and decision-oriented managerial perspectives with the more technical issues surrounding application and use of ecological indicators [66]. A summary of some of the objectives and necessary characteristics of good monitoring from the literature is presented in Table 2, most of which are voiced by Stohlgren et al. [64], who provide advice and "malpractice insurance" in the form of necessary characteristics of new monitoring programs. They express concern about the methods of large-scale forest monitoring programs, because field approaches at the plot-to-stand scales may not be suitable at landscape scales. And what exactly should be the objectives of a monitoring program? Regarding forest monitoring, Stout [67] says the primary objective is watching rates of change in a forest. More specifically, there is the need to decide which rates to observe and determine which are normal and which are abnormal. To do this, one needs to examine 1) the amount of variation, and 2) the scale over which variation occurs.

The premise of Cullen [68], that monitoring is necessary because we need to know information about the state of the environment both to help in choosing appropriate management action and in evaluating what our interventions have achieved is reflective of some of EMAP's objectives. Cullen conveys that the foundation underlying these objectives is that monitoring is necessary for: 1) assessing the effectiveness of policy or legislation, 2) regulatory purposes and, 3) detecting incipient change. Schindler [69] lists characteristics of successful monitoring programs: 1) they must be inexpensive enough to survive budget cuts in funding agencies 2) they must be simple and verifiable, so they are little affected by changes in personnel and, 3) they must include measurements which are highly sensitive to change in ecosystems. Good monitoring formats and bad formats (the "collect [data] now, think [of a good question] later" format) are described by Roberts [56]. Usher [57] proposes a hierarchical set of questions that should be answered when implementing a monitoring system:

Table 1. Summary of Objectives/Characteristics/Attributes of Environmental Monitoring Programs

Stohlgren et al. [64]	Millard [79]	Koskimies [128]
"Attributes of reliable long-term landscape-scale studies":	Among the many objectives of environmental monitoring:	Traits of effective national-scale bird monitoring:
1) secure long-term funding and commitment 2) develop flexible goals 3) refine objectives 4) pay adequate attention to information management 5) take experimental approach to sampling design 6) obtain peer review and statistical review 7) avoid bias in selection of long-term plot locations 8) insure adequate spatial replication 9) insure adequate temporal replication 10) blend theoretical and empirical models with means to validate both 11) obtain period program evaluations 12) synthesize retrospective, experimental, and related studies 13) integrate with larger and smaller scale programs 14) develop extensive outreach programs	- estimation of baseline physical or biological parameters - detection of standards violations - determination of the presence or absence of a change or impact in an area	- be continual - be done in same study areas from year to year - use comparable methods - cover as many species as possible - cover most of country - cover all habitats, both optimal and marginal - detect both short-term and long-term population changes - be scientifically valid - have high efficiency

Purpose: What is the aim of monitoring?
Method: How can this be achieved?
Analysis: How are the data, which will be collected periodically, to be handled?
Interpretation: What might the data mean?
Fulfillment: When will the aim have been achieved?

Landres [54] also stresses "question-oriented" monitoring, with specific questions driving and guiding the monitoring. In his stepwise methodology for a

Freedman [10]	Podlesakova and Nemecek [191]	Marko and Propperova [14]	Sanka and Paterson [15]
"Environmental monitoring programs *should*": - identify most important stressors that are recognized or threats to integrity - have a program in place to measure intensity or accumulated dose of the stressors over time - monitor or predict the response of organisms and ecosystems to change	"Characteristics carefully considered *by successful monitoring* programs": 1) spatial variability of environmental conditions monitored 2) characteristic substances and values reflecting the dominant processes, as well as the appropriateness of the methodologies and analytic procedures 3) the sampling frequency 4) criteria for evaluating the data obtained	"Basic concepts to be applied in monitoring *system for* the environment": 1) should be a multi-component, integrated, open, flexible system 2) framework must include linkages to other partial monitoring systems 3) effective coordination of methods, technical support, and procedures which stress data comparability 4) monitor at all levels—entire country, regional, local	"Important to ensure that all stages of *program be precisely* defined with rigorous protocols, including": 1) site location and sampling scheme 2) identification of characteristics to be monitored 3) sampling strategy, including frequency of sampling 4) preparation storage, and analysis of samples, including lab quality control 5) data processing, storage, and retrieval 6) interpretation of results and provision of advice to policy-makers

monitoring plan, Hinds [59] stresses the importance of properly designed monitoring plans and describes some of the difficulties of ecosystem-level monitoring as opposed to monitoring of organisms. Hinds states that while ecosystem measurements may be uniquely valuable, our current understanding of ecosystem processes is low, design development may be difficult at higher hierarchical levels, and replication is not clearly possible.

Although there is a need for comprehensive national-scale monitoring programs, there will still be in place many different monitoring programs from

Table 2. Comparison of Ecological Health Research and Human Health Diagnosis (Adapted from Rapport et al. [192])

Ecological Research Question Area	Analogous Human Health Area
Early warning indicators of ecosystem transformation	Early warning indicators of disease (e.g., the CEA carcinoembryonic antigen as an indicator of early intestinal cancer)
Exotic plant/animal/virus invasion or outbreak of native indigenous pathogens	Epidemiology
The presence of "sensitive zones" in ecosystems	The study of certain parts of the body that are crucial to functioning and well-being of the whole
Do ecosystems develop immunity to particular classes of combinations of stress?	Immune antibody responses to foreign antigens

many different agencies. Wilson et al. [70] attempt to deal with the diversity of monitoring programs as the purpose of their marine monitoring network in Canada is to integrate the time-series monitoring data of several federal and provincial agencies. This integration of data from many agencies will be a large task for those attempting to create centralized monitoring, because each agency may have different methodologies, resource classifications and measurements [35]. Wilson et al. [70] felt the work to integrate different monitoring networks was worthwhile; they hoped to improve the usefulness of the monitoring data by providing increased opportunity among different agencies for collaborative design. It may be difficult to create a single agency for monitoring. In the evolution of EMAP, originally intended to oversee all national environmental monitoring, there has been diminished emphasis on large-scale monitoring because it could be performed by other programs. Administrative turf wars between agencies already performing monitoring was likely involved.

O'Conner and Flemer [71] add discussion about relationships between management, monitoring and research, and stress again the importance of goals and objectives in developing monitoring programs. Historically, management agencies performing the monitoring have formed an "uneasy alliance" with the research institutions. O'Conner and Flemer [71] provide a rationale for making research and monitoring interdependent, with the foundation for this relationship being based on social values and goals. Once goals have been defined by management with public acceptance, the monitoring and research components can help evaluate the feasibility and long-term costs of achieving those objectives. Monitoring and research must be coupled to provide quality scientific guidance to decision-makers, and must be performed after temporal and spatial scales have been carefully considered [71-72]. To justify the large costs needed to measure variability on the spatial and temporal scales of key ecological processes, monitoring needs to be sharply focused. This integration of monitoring and research is a central issue for monitoring programs as descriptive knowledge is gained primarily through monitoring while functional knowledge, that which can ascertain causal relationships, is obtained primarily through hypothesis testing [71].

In the design of environmental monitoring programs, statistical considerations and a statistically-valid sampling design will play an increasingly larger role, especially if the intention is to characterize regional resource condition with a known confidence level [42; 73-78], and especially if it is important to detect changes on the same order of magnitude as the inherent variability [79], which may emanate from genetic variability of organismal populations, vagaries in ecological interactions, and random environmental influences [80]. Sanden and Danielsson [81], for example, failed to comprehensively characterize spatial pattern of surface water nutrients in the Baltic Sea, largely due to their uneven sampling in time and space. Millard [79] has noted the many technical problems of environmental monitoring programs, and links the resulting flawed or biased data analysis and policy decisions to the lack of involvement of qualified statisticians. He attributes part of this to the fact that ecological monitoring is a young field which may have yet to develop a statistical tradition comparable to that of, for example, the medical/pharmaceutical industry.

The data management aspect of monitoring is one area that also needs to be addressed in the pre-planning of monitoring [82, 83]. Michener [84] has noted the difficulties of several monitoring programs' integrated statistical and database management which include: 1) difficulty in accessing necessary statistical and graphical procedures, 2) inability to be flexible, in such ways as adding new variables or data sets to the database as research objectives change and, 3) maximal planning and effort required to get data online in accessible form. In addition, monitoring programs also need to have multivariate and cartographic/geographic analysis tools. Miller [58] discusses some of the past deficiencies of EPA's monitoring programs, mainly in relation to regulatory monitoring.

What constitutes ecosystem integrity is another question with which a national monitoring program must contend. Kay [85] provides a framework for assessing ecosystem integrity by determining how an ecological system is moved away from an optimum operating point due to changing environmental conditions. Karr [86-88] discusses biological integrity for water resources and maintains that monitoring and assessment should be guided by: the need to preserve human health; the need to preserve aesthetic, recreational, and other uses of biological systems for direct human benefit; and the need to preserve life support systems that provide both goods and services to human society through maintenance of healthy ecosystems. Steedman and Regier [89] list the following characteristics of ecosystems with regard to ecological integrity: 1) energetic in that natural ecosystemic processes are strong and not severely constrained; 2) self-organizing, in an emerging, evolving way; 3) self-defending against invasions by exotic organisms; 4) having biotic capabilities in reserve to survive and recover from severe crises; 5) attractive, at least to informed humans; and 6) productive of goods and opportunities valued by humans. Steedman [90] also notes a difference between the terms integrity and health: integrity best refers to sites with little or no influence from human action and health best describes the preferred state of sites modified by human activity. Some believe before we even get to the science of assessing ecological condition or "ecological health," the concept must be examined to see whether it can withstand critical scrutiny. Callicott [91] believes it can, but notes that we must be clear on our definitions regarding integrity and health.

Ecological indicators are an important part of the recent surge in interest in the ecological health concept, which is based on a human health analogy. Because ecological health cannot be measured directly, indicators of it are needed as surrogates of health status. While a full description of the ecosystem health debate is beyond the scope of this article, a good starting point is the work of David Rapport [92-94]. Others using the concept include Schaeffer [5, 95], who lists ecosystem attributes that can be considered as indicators of health. Many feel there are positive aspects to using the concept of ecological health and a human health metaphor [90, 39, 96, 97], while others have criticized the concept [98-100]. Ecological health is a condition of normality in the linked processes and functions that compose ecosystems. Biological integrity, meanwhile, is the capability of supporting and maintaining a balanced, integrated, adapted community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitats for the region. Integrity refers to conditions under little or no influence from human actions. In Callicott's conception, we can have ecosystems that have been greatly changed or even created by human action which can be healthy [91]. In some cases, integrity is considered to be within the realm of ecological health, and in other cases health is considered an aspect of integrity [101]. Karr [88] feels ecological health is inextricably connected to biological diversity and biological integrity. Clearing up any confusion about this terminology is important as other terms in ecology have multiple meanings: Pimm (cited in [53]) states that the word 'stability' among various ecologists refers to five different conditions.

The literature stresses the importance of connecting monitoring and the choice of indicators to human values. This makes monitoring all the more complex and difficult. When dealing with values, issues of a philosophical, scientific, statistical, economic, administrative, and practical nature all arise [54]. Relevance to issues of concern to humans is the most useful criterion in selecting indicators of ecosystem condition [102]. The Dutch and Swedes in particular rely heavily on social relevance of potential indicators in their monitoring programs [103-106]. Schroevers [107] emphasizes the need for ecologists to help define the notion of quality, not by imparting what is good or bad, but by providing the arguments necessary to make judgments. As Green [108] aptly asserts, "if the ecologist has not established any linkage between the public concern and the criterion variables used in his study, then it may be that nobody else will do it, either." To avoid meaningless data collection and wasted finances, a greater emphasis is needed on defining the questions to be answered by a monitoring program. Perry and others [109] declare that the primary objective of monitoring programs should be "asking the right questions at the right time and collecting only that data necessary to answer the questions." It seems that a good operating paradigm for environmental monitoring programs is the "question-oriented monitoring" called for by several scientists [54, 110].

ECOLOGICAL INDICATORS AND ECOSYSTEM RESPONSE TO ANTHROPOGENIC DISTURBANCES

The selection, use, and development of ecological indicators used to characterize the response of ecosystems to various stresses will be crucial to the success of EMAP and other monitoring endeavors [111]. We cannot feasibly measure all biotic and abiotic components of an ecosystem, which is the basic reason for use of an indicator [4, 112, 113]. Suggested research on characterizing ecosystem response to anthropogenic perturbation emanates from several sources. These include calls for increased understanding in the areas of long-term monitoring, ecosystem response to disturbance, "leading environmental indicators," ecological indicators, or status of the state of the environment [50, 114-123].

Ecological monitoring, which serves as the sensory tool for ecological risk management, is critical to the understanding of long-term trends. Of paramount importance in ecological monitoring/assessment programs is the concept of ecological indicators and the specific measurements used for these indicators. In general, indicators "are simply things that are believed to reflect, or "indicate" things that are not directly measurable" [124]. An indicator is defined as a characteristic of the environment that when measured, quantifies the magnitude of stress, habitat characteristics, degree of exposure to a stressor, or degree of ecological response to the exposure [2]. An alternate definition is that of the U.S. Council of Environmental Quality in Sheehy [33]: an environmental parameter, theoretical concept, or aggregation of data that provides a surrogate representation of some aspect of environmental quality or condition. An indicator is a tool to:

1. monitor the status of the environment and its evolution over time,
2. evaluate the performance of projects, programs, and plants,
3. communicate with the public and between decision-makers,

4. identify areas of action, and
5. help in the development of future planning procedures.

Thus, the concept of ecological indicators has evolved from not only including analysis of bioaccumulation of xenobiotic material in organisms or presence/absence of individuals or species, but also to indicators of total system functioning and structure. Moreover, indicators of ecological condition are being focused increasingly on biological parameters rather than merely physical and chemical measurements [35, 44, 61, 86, 87, 125-129]. Roux and others' [44] argument for biological monitoring partly explains this trend in regional water quality assessments. They list advantages of assessing biological components of the environment which include:

1. overall ecosystem integrity is reflected by biological communities,
2. effects of different contaminants are integrated by biological communities: a holistic measure of total impact is provided,
3. biological monitoring is relatively inexpensive when compared to the cost of comprehensive chemical assessment of microcontaminants,
4. chemical pollutant loading is not easily understood by the public, while status of biological communities is of direct interest to the public and,
5. biological communities may be the only means of evaluating certain impacts for which criteria do not exist (e.g., non-point source pollution) (also mentioned in [45]).

Their conceptual outline of a program assessing ecosystem health has four main components: 1) a background study (primarily determining land use), 2) physical/chemical variables, 3) habitat assessment and, 4) biomonitoring, which will include bioassessments, bioassays, fish health studies, and bioaccumulation studies.

Currently, the indicator concept is also being suggested to aid the global climate research change agenda [130-131]. Indicators are intended to complement the current climate change model being used, the predictive model framework. In some cases, perfectly accurate predictions of change are impossible, as ecological systems may adapt in unforeseen ways. The objectives of a systems response framework incorporating indicators in climate research are to:

1. identify climate sensitive ecosystems, processes, landscapes, and populations where signs of disorder can be observed as early as possible,
2. develop and apply methods to identify signs of disorder within these sensitive systems (e.g., vegetation, organism distributions, etc.) and,
3. combine such information into indicators that provide evidence of disorder responses to global climate change and disorders to come if the rate of climate change continues to accelerate [130].

Much of the literature on the assessment of ecological condition and stress ecology discusses generalized responses of ecosystems to stress and should prove helpful in deciding which ecological parameters to choose as indicators for quantifying the degree of stress and thus indicating condition. Woodwell [132] is among the earliest of researchers to generalize ecosystem and community response to pollutants. His hypotheses stem from experiments on the effect of ionizing radiation on an oak-pine forest community. Odum [133] categorized eighteen generalized responses (trends) of ecosystems to stress in four areas:

1. Energetics
   - community respiration increase
   - production/respiration becomes unbalanced (< or > 1)
   - production/biomass and respiration/biomass (maintenance:biomass structure) ratios increase;
   - importance of auxiliary energy increases; and
   - exported or unused primary production increases
2. Nutrient Cycling
   - nutrient turnovers increase
   - horizontal transport increases and cycling of nutrients decreases; and
   - nutrient loss increases (system becomes more leaky)
3. Community structure
   - proportion of r-strategists increase
   - size of organism decreases
   - lifespans of organism or parts (e.g. leaves) decrease;
   - food chains shorten because of reduced energy flow at higher trophic levels and/or great sensitivity of predators to stress; and
   - species diversity decreases and dominance increases; if original diversity is low the reverse may occur; at the ecosystem level, redundancy of parallel processes theoretically declines.
4. General Systems level trends
   - ecosystems become more open (i.e. input and output environments become more important as internal cycling is reduced)
   - autogenic successional trends reversed (succession reverts to earlier stages);
   - efficiency or resource use decreases;
   - parasitism and other negative interactions increase, and mutualism and other positive interactions decrease; and
   - functional properties (such as community metabolism) are more robust (homeostatic or resistant to stressors) than are species composition and other structural properties.

Odum's hypothesis is that a disturbance to which a community is not adapted reverses autogenic development. Schindler [69, 134] has compared these eighteen generalizations to actual responses to acidification observed in experimental lakes. Verifying some of these trends in real-life situations may prove difficult, however, as results showed that some variables reflecting ecosystem properties were not changed. Primary production, nutrient cycling and respiration were considered poor indicators of early stress. None of the trends as stated by Odum for energetics and nutrient cycling were observed. Periphyton metabolism was the most sensitive indicator while ecosystem-level production and respiration were the most resistant properties to stress. Schindler suggests that if low-level detection is desired, there is a need for increased emphasis on studies of population dynamics, food-web organization, and intraspecies adaptation.

Other examples of the use of indicators are from Davis [43], who includes assessments of pollutants and natural constituents, and the following measures of population dynamics and biodiversity: abundance, distribution, age structure, reproduction, effort, and growth rate. Most of these are sensitive to subtle, chronic stress, and allow projection of future conditions. Davis [43] presents a framework for organizing a monitoring program and emphasizes that simple repeated inventories of biota do not meet the goals of diagnostic monitoring. One must couple these with data on appropriate physical and chemical measurements in order to determine causality. Bruns et al. [37] believe a small subset of parameters can be used in environmental assessments. These include levels of population, community, and ecosystem functioning and include: abundance, reproduction, and behavior, trophic relationships, species diversity, successional change, size relationships, and energy flow, nutrient cycling, decomposition/respiration, and biomass nutrient pools.

A framework by Lefroy and Hobbs [135] may be useful in deriving indicators of ecological sustainability in agroecosystems. In their proposed system for evaluating Australian agroecosystems, indicators are designed to reflect conditions in four fundamental components: 1) cycling of water, 2) cycling of nutrients, 3) flow of energy and, 4) role of species richness. Our lack of understanding of soil processes was noted as the difficulty for simply derived indicators measuring condition. This lament over lack of complete understanding of ecosystem processes and dynamics appears to be common in research of many systems. Lefroy and Hobbs [135] provide a list of parameters (general indicator categories) and indicators (specific measurements).

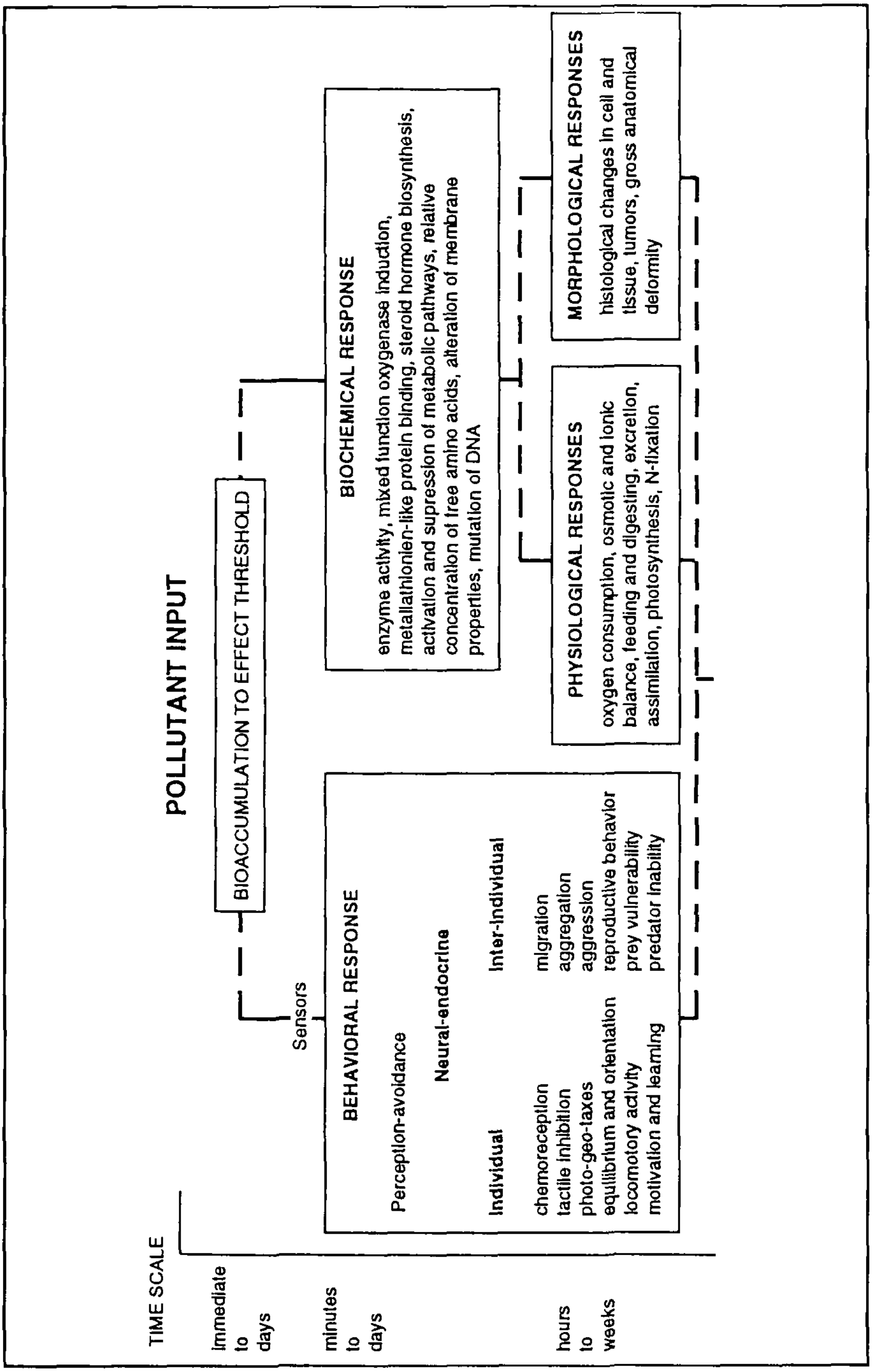
APPLICATION OF ECOLOGICAL INDICATORS

Ecological systems are considered to be hierarchical in nature. Accordingly, there are several levels of scale on which indicators can be used. Sheehan [136, 137] and Miller [138] diagram the responses of ecological systems to toxic pollutants at varying temporal (days to centuries) and spatial scales: cellular/physiological, individual, populations, and communities/ecosystems/landscapes (also adapted by de Kruijf [139]) (Figure 1). Kimmins [140] also provides a review of lower hierarchical level indicators (physiological and species). Taub [141] comments on assumptions and generalizations surrounding the implementation of indicators of environmental change and recommends new research on promising indicators of change. Taub questions such assertions as "human impacts will have different indicators than natural impacts," "all ecosystems will respond in the same manner to stress," and "a magic index exists that requires no detailed study."

Kelly and Harwell [102, 142] provide a thorough overview of the mechanisms involved in ecological disturbance and the issues surrounding evaluation of anthropogenic stress on the environment including exposure, response, recovery, and uncertainties in analysis (resulting from variability in exposure and ecosystems, and extrapolation across types of stress and ecosystems). They present the basics for analyzing ecological disturbances within the framework of ecological risk assessment, and distinguish between four different purposes of indicators: intrinsic importance, early warning indicators, sensitive indicators, and process indicators. Intrinsic importance refers to valuable species, endangered species, or other aspects of direct importance to humans. The primary importance of early warning indicators is their rapid indication of effect. These types of indicators can be used as "red flags" to alert attention to a possible problem. Sensitive indicators focus on actual responses rather than potential ecological effects. In this case, there should be a strong specificity to a type of stress. Process indicators highlight change in ecological functions and processes. These indicators could also serve as early-warning or sensitive indicators. Indicators of ecosystem vulnerability focus on both abiotic and biological aspects and include geochemical character, presence of physical refugia, linearity of food webs leading to a major species, etc. De Kruijf [139] also discusses these same issues while adding a discussion on extrapolation of effects at lower levels of biological organization to higher levels. Harwell and Harwell [143] examine the complexity of ecosystem response to chemical exposure by discussing direct biological effects, indirect biological effects, ecosystem level effects, and extrapolation issues. Johnson [144, 145] analyzes ecosystem response to stress by representing ecological parameters as multidimensional state vectors in a Cartesian space.

The use of animals as indicators of ecosystem properties and responses, specifically to air emissions, is presented in Newman and Schreiber [146], in which a reference list for specific case studies is also provided. Indicators of biodiversity are provided by Noss [147], Williams and Marcot [148], and Reid et al. [149]. Other literature provides specific environmental parameters (indicators) used in monitoring avian species [128], wilderness areas [150, 151], forests [30], national parks [152], national forests in the Great Lakes region [153], and general ecological condition in The Netherlands [154]. Keddy [155] reports on some of the issues surrounding indicators, including the selection of indicators and monitoring in relation to environmental prediction and decision making.

Seabirds provide an example of how animals can be used as indicators of ecological conditions at meso- or macro-scale. Through aspects of breeding and feeding ecology, monitoring of seabirds should reflect seasonal or interannual changes in the productivity of oceans [156]. In deciding which species to select for monitoring purposes Silsbee and Peterson [157] suggest species should be:


TIME SCALE
immediate to days
minutes to days
hours to weeks
POLLUTANT INPUT
BIOACCUMULATION TO EFFECT THRESHOLD
Sensors
BEHAVIORAL RESPONSE
Perception-avoidance
Neural-endocrine
Individual
chemoreception
tactile inhibition
photo-geo-taxes
equilibrium and orientation
locomotory activity
motivation and learning
Inter-individual
migration
aggregation
aggression
reproductive behavior
prey vulnerability
predator inability
BIOCHEMICAL RESPONSE
enzyme activity, mixed function oxygenase induction, metallathionien-like protein binding, steroid hormone biosynthesis, activation and supression of metabolic pathways, relative concentration of free amino acids, alteration of membrane properties, mutation of DNA
PHYSIOLOGICAL RESPONSES
oxygen consumption, osmotic and ionic balance, feeding and digesting, excretion, assimilation, photosynthesis, N-fixation
MORPHOLOGICAL RESPONSES
histological changes in cell and tissue, tumors, gross anatomical deformity

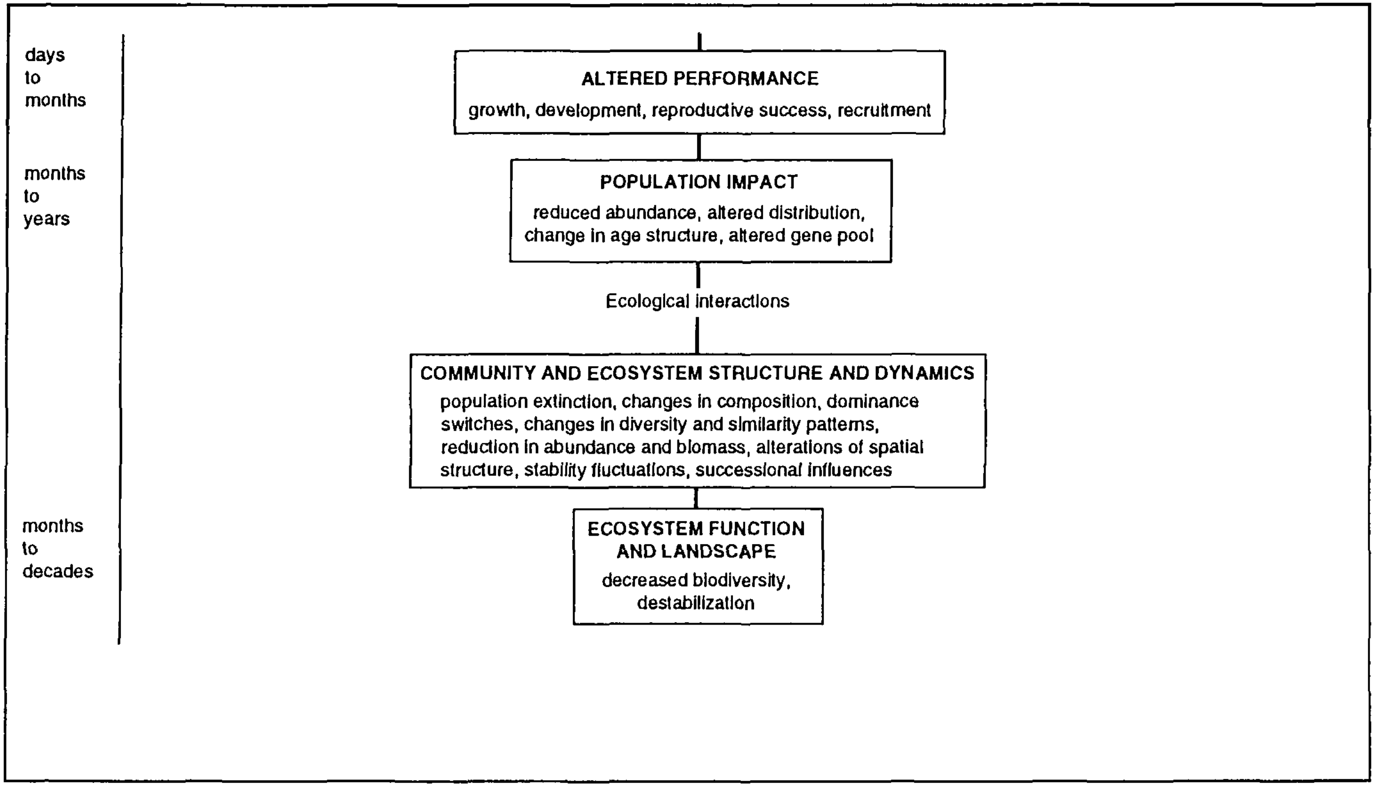


Figure 1. Generalized framework of biological/ecological effects of contaminants at various hierarchical levels.
Source: Sheehan et al. [136] and adapted from de Kruijf [139].

1. widespread, dominant, or important in controlling ecosystem functioning (significant to overall ecosystem),
2. rare, endangered, or endemic (because of vulnerability),
3. known to be in flux (to keep track of known cases of change),
4. disturbance dependent (because it is likely to be in flux and may require management intervention),
5. alien species (because it is considered a threat), and
6. charismatic (because of public support and understanding).

Hanley [158, 159] states that the black-tailed deer is an excellent indicator of ecological condition in southern Alaskan forests because:

1. their biology and ecology is well-known,
2. they have relatively large seasonally migratory home ranges and so require management of landscapes,
3. their need for productive and nutritious supply of food which makes them largely dependent on old-growth forest and,
4. they are an important game species in the subsistence economy of rural residents.

Palmer [160] stresses caution in monitoring rare species simply because most are temporally autocorrelated; if one sees rare species at the start of monitoring, one will on average falsely conclude that the most threatened species are becoming more common through time. The use of current rarity, abundance, or homogeneity as selection criteria can cause the appearance of trends when in fact none exist. So they suggest in addition to monitoring rare species, infrequent species should also be monitored. Landres [54] and Landres et al. [161] are discouraging in their assessment of the use of indicator species as they "may bear no direct or simple cause and effect relationship to the factor or factors of interest." They provide a critical and rather harsh review of the current beliefs and assumptions of those currently employing indicator species. Cairns et al. [162] list the disadvantages of using indicator species in toxicology tests to assess the health of the environment:

1. The system is based on solid knowledge of responses of organisms to pollution. Many species on earth are not yet named and their indicator status is not known.
2. The response of organisms to impact is not uniform across stress type.
3. Environmental protection must assure that organisms are robust and healthy rather than merely just surviving.
4. The approach is reactive as it records rather than prevents change.

Breckenridge et al. [22] excluded faunal indicators in their rangeland assessment program because many experts felt that animals in general may not be as directly diagnostic of changes as other indicators. Morrison and Marcot dispute the following basic reasoning of those using animals as indicators:

> if overall conditions are good, then an indicator of those conditions will take on particular values; if the indicator is observed to not take on those values, then the environmental conditions are not good.

The problem, they believe, is that indicators can react to a variety of factors other than those that represent the environmental conditions of interest. Hence, one cannot be positive that the indicator directly and always reflects local conditions or the direct effect of land management [113].

CRITERIA OF GOOD INDICATORS

The selection of indicators for characterizing ecosystem condition and their ongoing evaluation will be an integral part of an environmental monitoring program [111]. Indeed, some believe that the choice of measurements (indicators) selected acts as a keystone in framing environmental problems [163]. This will be very important if most of the time spent on problem-solving is used for answering the wrong questions, stating problems too generally, or determining what the question is [164]. A summary of criteria for indicators expressed in the literature is provided in Table 3. Herricks and Schaeffer [60] provide criteria for "measure" selection, with particular emphasis on biological measures. Schaeffer and others [5] provide criteria for determining general ecosystem health and the measures by which to assess it. Rapport [165] provides the "three Rs" for a good indicator: relevance, robustness, and reliability. Krantzberg [166] and Day [167] provide criteria for indicators with reference to the Canadian State of the Environment Program. Liverman [168] provides criteria for desirable global sustainability indicators. Frost [169] states that indicators may have two desirable but possibly contradicting properties: 1) sensitivity to a variety of anthropogenic stresses and 2) predictability in unperturbed ecosystems. Since sensitive parameters may show some degree of unpredictable variability, the choice of ecological indicators will involve compromising these two factors. Other authors synthesize various listings of criteria of good indicators [33, 162, 170, 171]. Additional criteria of indicators provided by Wessels Boer in Sheehy [33] include:

1. Results of monitoring programs should not excessively depend on irrelevant changes, such as local changes of weather.
2. Cost of measurements and monitoring program as a whole should correspond to importance of results.
3. Sensitivity of measurements should correspond to accuracy required to support policy decisions.
4. Results of monitoring program should be related to established norms—i.e., results should be evaluated to allow a classification into categories of permissible/not permissible or desired/not desired.

Table 3. Criteria for Selection of Successful Ecological/Environmental Indicators

Kelly and Harwell [102]	Schaeffer et al. [5]	Liverman et al. [168]
"Criteria for selecting indicators"	"Basis for an initial assessment of ecosystem health"	"Criteria for desirable global sustainability indicators"
Signal-to-noise-ratio - Sensitivity to stress - Intrinsic stochasticity	Should not depend on presence/absence or condition of a single species	Sensitivity to change in time
Rapid Response - Early exposure - Quick dynamics - Stress-specific sensitivity	Should not depend on a census or even inventory of large numbers of species	Sensitivity to change across space or within groups
Reliability of Response - Specificity to stress	Should reflect our knowledge of normal succession or expected sequential changes which occur naturally in ecosystems	Predictive ability
Ease/Economy of Monitoring - Field sampling - Laboratory expertise - Preexisting database and history - Easy test for process	Does not have to be measured as a single number	Availability of reference or threshold values
Relevance to Endpoint - Intrinsic - String of ecological connections	Should assure that measures have a defined range	Ability to measure reversibility or controllability
Feedback to Regulation or Management - Adaptive management potential - Hierarchical suites of indicators	Should be single-valued (monotonic) and vary in a systematic and discernible manner	Appropriate data transformation
Relevance to Recovery Processes - Short-term and long-term processes - Refugia, colonizing capacity - Adaptation to new physical constraints	Should be responsive to change in data values but should not show abrupt changes even when values change by several decades	Integrative ability
	Should have known statistical properties if relevant	Relative ease of collection and use
	Must be related and hierarchically appropriate for use in ecosystems	
	Should be dimensionless	
	Should be insensitive to the number of observations, given some minimum number of observations	

Herricks and Schaeffer [193]	Bruns et al. [150]	Suter [194, 195]
"Criteria for biomonitoring data selection"	"Criteria for evaluation of environmental monitoring parameters for a wilderness ecosystem"	"Characteristics of good measurement endpoints"
Must be biological or have proven relationships to biological-ecological effect in the system	Have an ecosystem conceptual basis	Corresponds to or is predictive of an assessment endpoint
Must *be amenable to appli*cation at other trophic levels, reflect effects at other levels of the biological-ecological hierarchy, or provide an experimentally verified connection to other organisms or trophic levels	Data Variability	Is readily measured
Must be sensitive to the environmental conditions being monitored - Sensitive to small magnitude changes - Have a range of response that will allow differentiation of effect from consequences	*Uncertainty*	Is appropriate to the scale of the site
Response range of the measure must be suitable for intended application	Useability	Is appropriate to the exposure pathway
Must be reproducible and precise within defined and acceptable limits	Cost-effectiveness	Has appropriate temporal dynamics
Variability of the measure must be low		Has low natural variability
		Is diagnostic
		Is broadly applicable
		Is standard
		Has existing data series

Table 3. (Cont'd.)

Rapport [165]	Day [167]	Krantzberg [166]
"Criteria of well-chosen environmental indicators"	"Criteria to be used for evaluating indicators of marine and Great Lakes Environmental Quality"	"Characteristics of indicators used for Canadian State of the Environment Report"
Relevance - Socially desirable	Can be applied nationally or over broad biophysical regions	Must reflect SOE (State of Environment)
Reliability	Scientifically defensible	Must be understood by policymakers
Robustness	Adequate historical record and projected availability of ongoing/future data	Shoud be used by scientists to compile the SOE report, but should still be interpretable by decision makers
	Reliability and consistency of types of measurements used to assess indicators	Should include a range of indicators as any indicator will not be universal
	Simplicity - Of measurement and interpretation	
	Data generally should be quantitative	

Miller [138]	Udo de Haes et al. [154]	Riitters and Barnard [173]
"Desirable properties of parameters for assessing change in ecosystems"	"Criteria for selecting 'environmental quality' criteria in The Netherlands"	"Criteria to evaluate forest health indicators"
Indicative of overall condition of the ecosystem Comparable for a variety of ecosystems Easily and reliably measured	Relevance to environmental policy Sensitivity Detectability Appeal - To laypersons, policymakers, etc.	Strategic value - Be part of broader plan for assessing changes in forest health Tactical value - Provide useful information for different types of health assessment Scientific value - Should be chosen from biological models that lend realism and that are interpretable

Table 3. (Cont'd.)

Frost [169]	Kreisel [196]	Lubchenco et al. [116]
"The choice of ecological indicators:"	Characteristics of environmental indicators used in an environmental quality profile of a metropolitan area	"Ideally indicators would be chosen on basis of:"
Must balance: - Sensitivity and - Predictability	Valid - Actually measure what they are supposed to measure	Speed of their response
		Sensitivity to specific stressor
	Objective - Should be same if measured by different people	Ability to optimize sensitivity and variability
	Sensitive	
	Specific - Reflect changes only in the situation concerned	

Marshall et al. [172]	Landres [161]	Gilbert and Feenstra [104]
Criteria of an ideal indicator organism to represent ecosystem health in the Great Lakes	"Ecological criteria for selecting vertebrate indicator organisms"	"Desired features of an indicator"
Baseline historical records on abundance available Be an integrator of the community in which it plays a key ecological role Have a wide distribution Have extensively quantified and well-developed niche envelope Have habitat requirements that are comprehensively understood and documented Exhibit at least a moderate degree of phenotypic diversity Be susceptible to, or reflect in various ways, most interventions of cultural origins Have a high human value and a ready recognition by humans	Sensitivity - Should be sensitive to contaminants or attributes of concern Variability of response - Should be low Specialist vs generalist - Should demonstrate relationship to habitats of interest and not just be chosen solely on whether they are a specialist or generalist Size/population turnover and species turnover - Both small and large species may be necessary for assessments over both short- and long-time scales Residency status - Should be permanent residents Area requirement - Area per se is a tenuous criterion unless research confirms that a species with a large home range can serve as an indicator of habitat quality or of an entire community in that particular location	Indicator must be representative for chosen system and have scientific basis Indicators must be quantifiable A part of the cause-effect chain should be clearly represented by the indicator Indicators should offer implications for policy

For future work, rather than compile more "lists of indicators," it would be a good idea to create an integrated systemic framework within which such indicators can be developed [124]. Breckenridge et al. [22] detail their selection of indicators for assessing rangeland health. Before implementing their program, organizational steps consisted of:

1. Selecting environmental values of concern to society. Thus they addressed issues on: extent and distribution of a particular resource class on a regional scale, proportion of the area in different productivity categories, changes or trends between and among productivity categories, and soil quality.
2. Selecting a system for classifying vegetation.
3. Selecting general indicator categories.

After indicator categories were selected, a series of workshops were held among experts to determine the final set of indicators and measurements to be used. However, even after this point, rigorous evaluation of the indicators and results obtained from them must take place. Their overall effectiveness must be assessed with regard to selection criteria, with the list of indicators flexible and changing over time as new research and technology allow new and improved indicators to be developed. Bruns et al. [150] assign subjective scores of 0 to 2 to indicators in various categories based on how they meet certain criteria (see Table 3). This procedure allowed them to rank the overall effectiveness of indicators used in monitoring stream conditions.

Marshall and Ryder [172] provide criteria for selecting animals as indicators of ecosystem health, specifically referring to the Great Lakes system. Kelly and Harwell [102] distinguish between two types of indicators: screening indicators (to act as a red flag) and state-specific indicators. Riitters and Barnard [173] provide indicator criteria for the assessment of forest health: strategic value, tactical value, and scientific credibility.

A common requirement is that indicators represent processes governing at different time and spatial scales, as changes are taking place at many scales [64, 174, 175]. This is recognized in bird monitoring [128], fish population monitoring [176], and water quality monitoring [177, 178]. At different scales, different variables are often needed to describe similar processes. One can arrive at very different conclusions about whether a system is stressed by extending or contracting spatial or temporal boundaries [179]. The scale of the measurement must match the scale of the process that is being used as an indicator [75]. Another important consideration is the ability to be merged with other data sets to make integrated assessments of ecological condition possible at the regional level.

CONCLUSION

A rich literature exists on the concepts of ecological monitoring and ecological indicators. As monitoring achieves increased stature and importance, environmental scientists and managers involved in ecological monitoring and indicators should familiarize themselves with the literature reviewed here when conducting ecological assessments via monitoring programs. As this review has shown, the most critical aspects of monitoring are neither the physical collection of data nor the data analysis, logistics or technical equipment as one might guess, but the pre-planning goal and objective formulation, and rationale for choosing indicators.

Although the concepts are discussed frequently, the use of such specific terms and keywords as ecological indicator and ecological health appear to be relatively new and not yet common in the scientific and environmental literature. The development of ecological indicators at the ecosystem level and on a regional scale is a science in its infancy, and accurate indicators of ecological condition are still being determined [180]. Nonetheless, literature is rapidly being produced in the subject area and more articles directly addressing the issue will undoubtedly appear in the coming decade. For future literature searches where more detailed or mechanism-specific indicators are desired, the approach suggested by American Management Systems [181] may prove fruitful. For obtaining a more thorough search of the term "endpoint," they suggested searching a desired stressor (e.g., acid rain), in which case an abundance of literature exists, most likely including effects on ecosystem processes and structure (which could be considered indicators of stress).

Regardless of the actual indicator choices, an adequate monitoring system designed to assess ecological condition on a regional scale will consist of a multivariate suite of indicators integrating biological, chemical, and physical measures and integrating hierarchical levels [3, 5, 10, 35, 86, 102, 126, 182-188] rather than placing inordinate emphasis on any one or two indicators. The use of only one or two forest health indicators in Europe was a basic error in forest health monitoring in the 1980s [184]. Based on much of the literature, one can expect monitoring programs to be dynamic and not static because:

- concern over the types of impacts will change as restoration activities succeed in their goals and new forms of impact are identified and quantified,
- results of basic research and surveillance programs will undoubtedly modify the suite of parameters deemed most useful for evaluating ecosystem health, and
- ecosystem goals and objectives will continue to be developed and refined to meet the broad and changing demands of various shareholders [40].

The societal values upon which these goals are based may also be changing [184]. Thus monitoring must also be 'adaptive' and flexible, following the approach of 'adaptive ecosystem management' [189, 190].

SUGGESTED FUTURE DIRECTIONS

The review of this literature on ecosystem monitoring and indicators of ecological condition has revealed a great variety of information on general responses of ecosystems and foundations for a good monitoring program. Ecologists need to work towards defining what is "good" ecological condition and to determine how useful or misleading the "ecological health" analogy is. Although scientists and environmental managers promoting the ecological or ecosystem health concept do not regard ecosystems as organisms, there still exists the notion among some professionals that this abstraction connotes an ecosystem/human medicine analogy which may prove misleading when communicating environmental information to the public. The debate over the issue of whether ecological monitoring and assessment should be a purely scientific endeavor or whether it should incorporate social values also needs to be resolved. As shown in this review, most have leaned toward the inclusion of social values. However, scientists will also have to deal with the fact that social values will be changing and determine whether it is certain that these values will be biologically achievable [184].

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